# FLUX OF LARGE METEOROIDS FROM LUNAR IMPACT MONITORING AND INFRASOUND

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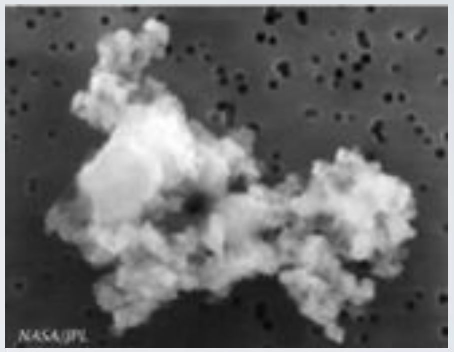
Meteoroid - small rocky/ icy debris out in space



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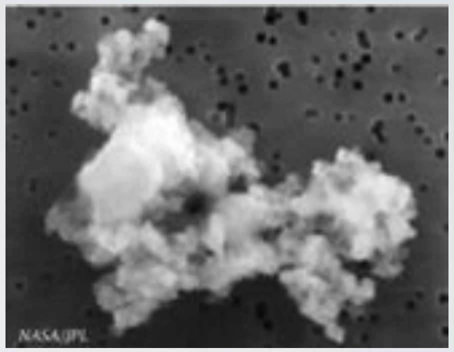



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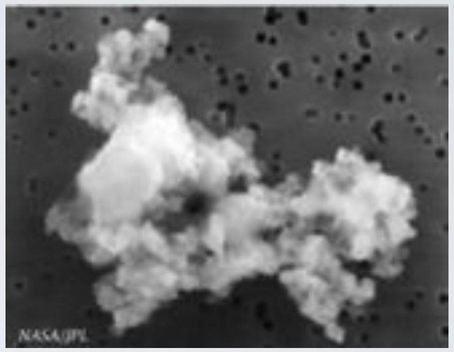
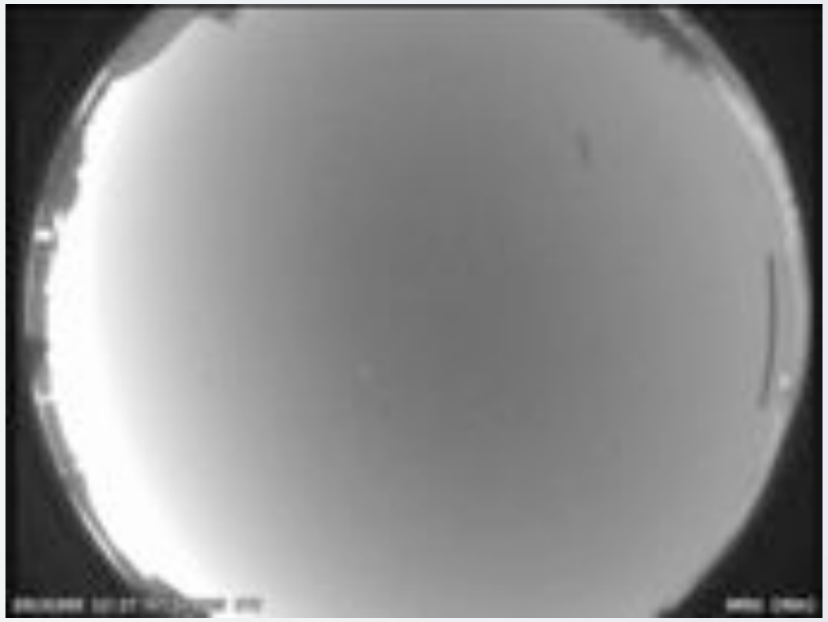


Meteor - streak of light/ionization produced by a meteoroid ablating in an atmosphere

Fireball - meteor with a peak brightness greater than the planet Venus ($m_v$ -4). Also called a bolide




Super bolide - a meteor sufficiently energetic to be detected by seismic/other sensors ($m_v$ ~-18)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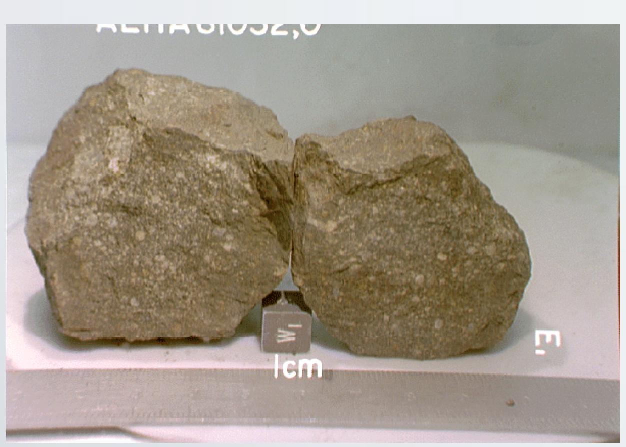


Meteorite - any part of a meteoroid/ asteroid that makes it to the surface

# ASTEROID OR METEOROID?

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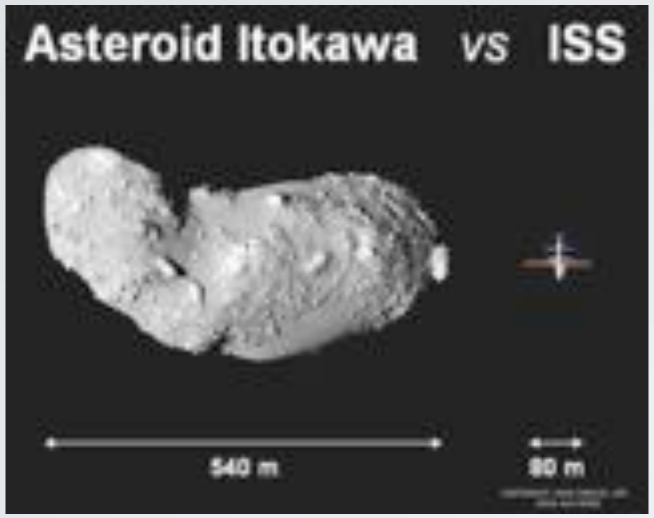
International Astronomical Union definition: "A meteoroid is a solid object moving in interplanetary space, of a size considerably smaller than an asteroid and considerably larger than an atom."

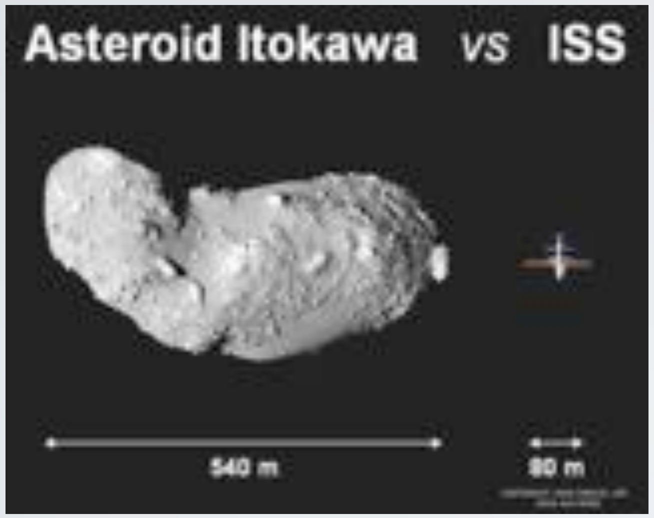
# How NASA handles meteoroids, asteroids, and space junk




Earth-approaching asteroids

Near Earth Object Office (JPL)

# How NASA handles meteoroids, asteroids, and space junk



Earth-approaching asteroids

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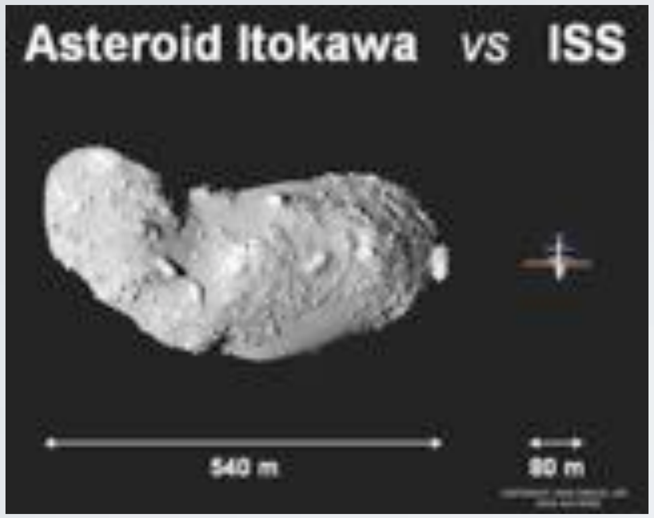
Man-made orbital debris

Orbital Debris Program Office (JSC)

# How NASA handles meteoroids, asteroids, and space junk




Earth-approaching asteroids

**Near Earth Object Office (JPL)**

Meteoroids and meteors

**Meteoroid Environment Office (MSFC)**

Man-made orbital debris

**Orbital Debris Program Office (JSC)**

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Provide meteor shower forecasts to NASA/USG spacecraft operators

Monitor the meteoroid environment in near-Earth space (SSA)

Conduct and manage research to improve sporadic and shower meteoroid models

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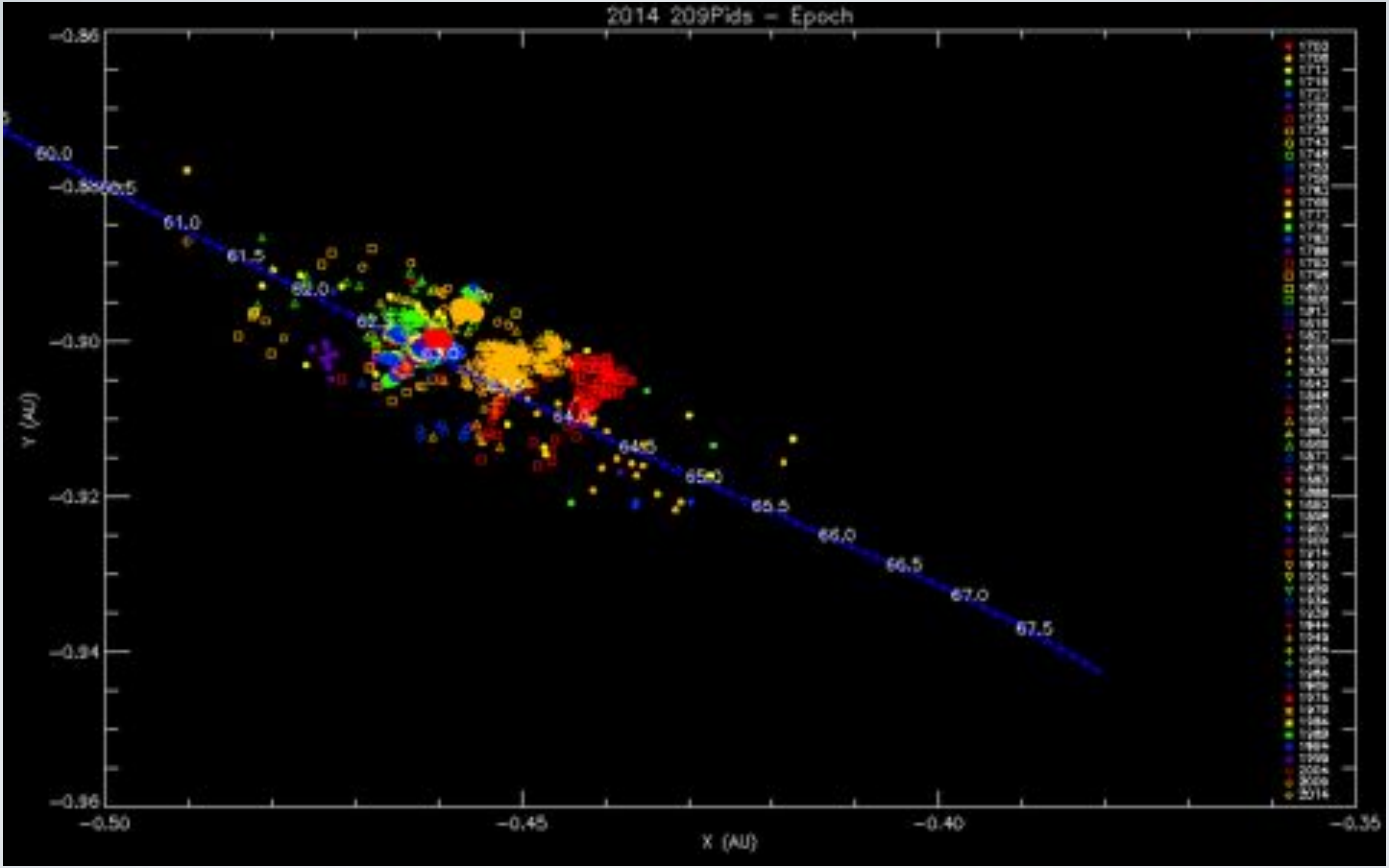
Models indicate mm size particles in stream, so potential risk to Earth orbiting spacecraft

| Model | Time on May 24 (UT) | ZHR (#/hr) | RA, Dec (°) | $V_g$ (km/s) |
|---|---|---|---|---|
| Lyytinen & Jenniskens (1929) | 3:19 | | | |
| Lyytinen & Jenniskens (1979) | 6:04 | | | |
| MSFC (peak 1) | 6:11 | | | |
| Lyytinen & Jenniskens (1818, 1853) | 6:33 | | | |
| MSFC (peak 2) | 6:56 | | | |
| Lyytinen & Jenniskens (1903, max) | 6:59 | 15.86 | 125, +78 | 15.86 |
| Lyytinen & Jenniskens (1909) | 7:15 | | | |
| Maslov (1898-1919; 1903) | 7:18 | 200-300 | 122.8, +79.1 | 16.2 |
| Maslov (max) | 7:21 | 100 | 122.8, +79.0 | |
| Vaubaillon | 7:40 | 100-400 | ~125, +79 | |
| Lyytinen & Jenniskens (1914) | 7:49 | | | |
| Maslov (1763-1783) | 7:55 | 50-150 | 122.8, +79.0 | 16.2 |
| MSFC (peak 3) | 8:10 | | | |
| Jenniskens (general) | | | 123, +79 | 16 |


2014 209Pids - Epoch
Y (AU)
X (AU)
-0.86
-0.88
-0.90
-0.92
-0.94
-0.96
-0.50
-0.45
-0.40
-0.35
60.0
61.0
61.5
62.0
64.0
64.5
65.0
65.5
66.0
66.5
67.0
67.5


NASA
National Aeronautics and
Space Administration
4347
ENGINEERING DIRECTORATE
Automated Lunar and
Meteor Observatory

# 7-year observing program

Goal: Monitor the Moon for impact flashes produced by meteoroids striking the lunar surface.

Observation from MSFC

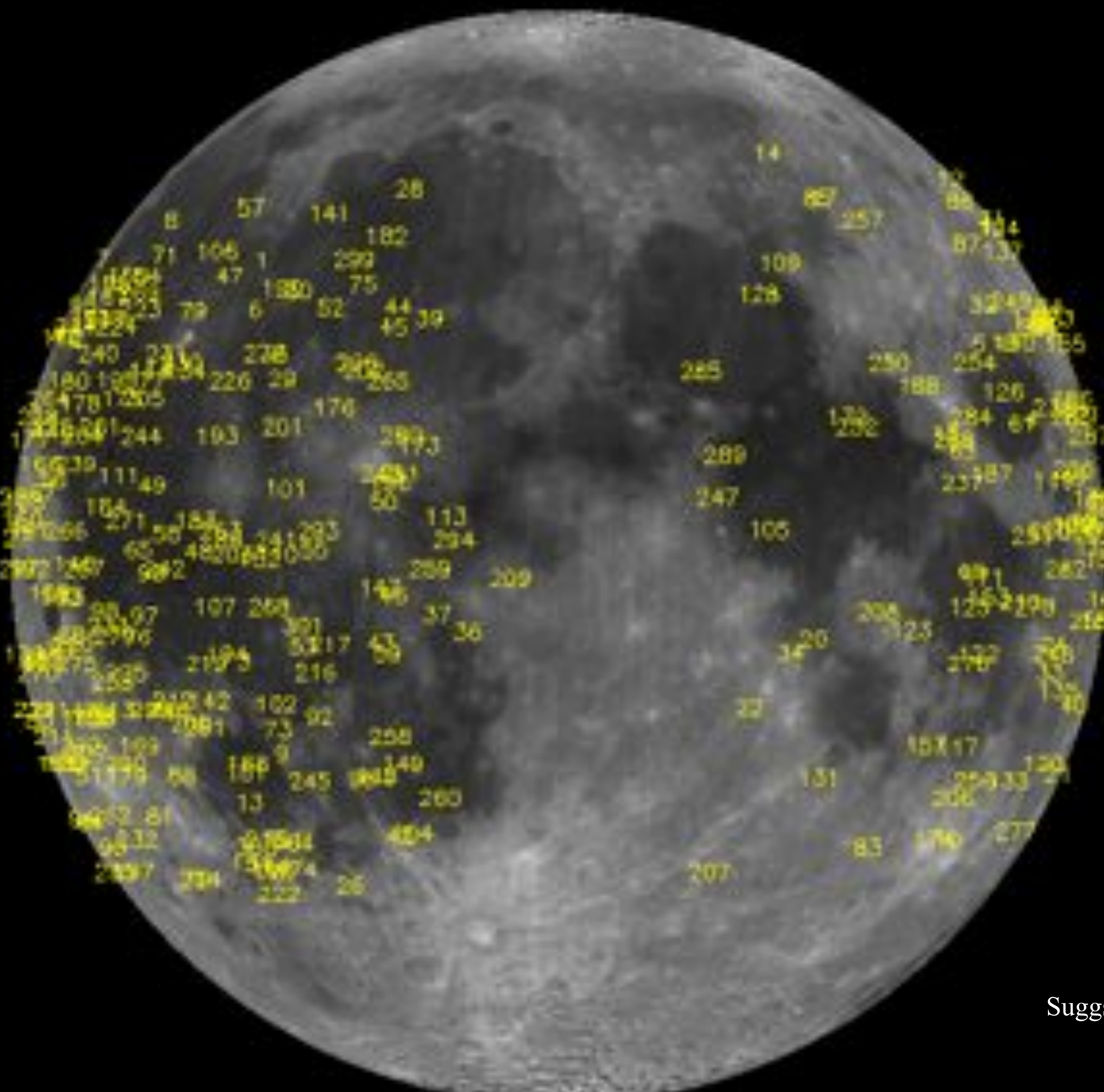
- Two 0.35m telescopes simultaneously
- Black & white CCD video cameras
- Interleaved 30fps video digitized, recorded
- Video analyzed with custom software


Field of View

- FOV covers approx. 20 arcmin
- $4{\times}10^6$ $km^2$ on the leading or trailing edge
- Observing when illumination 10-50%
- Maximum 10 observing nights/month

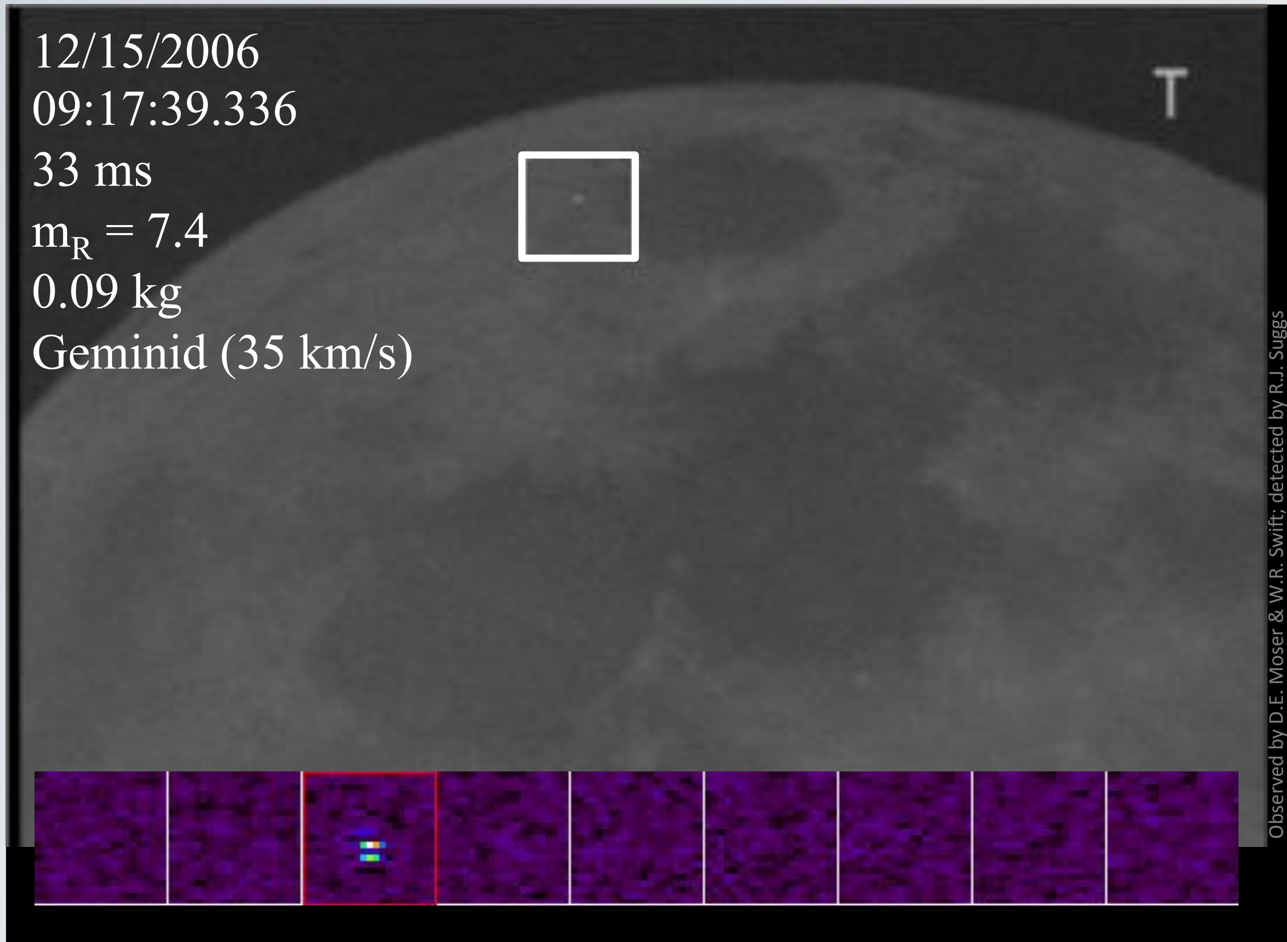
# 300+ lunar impacts observed

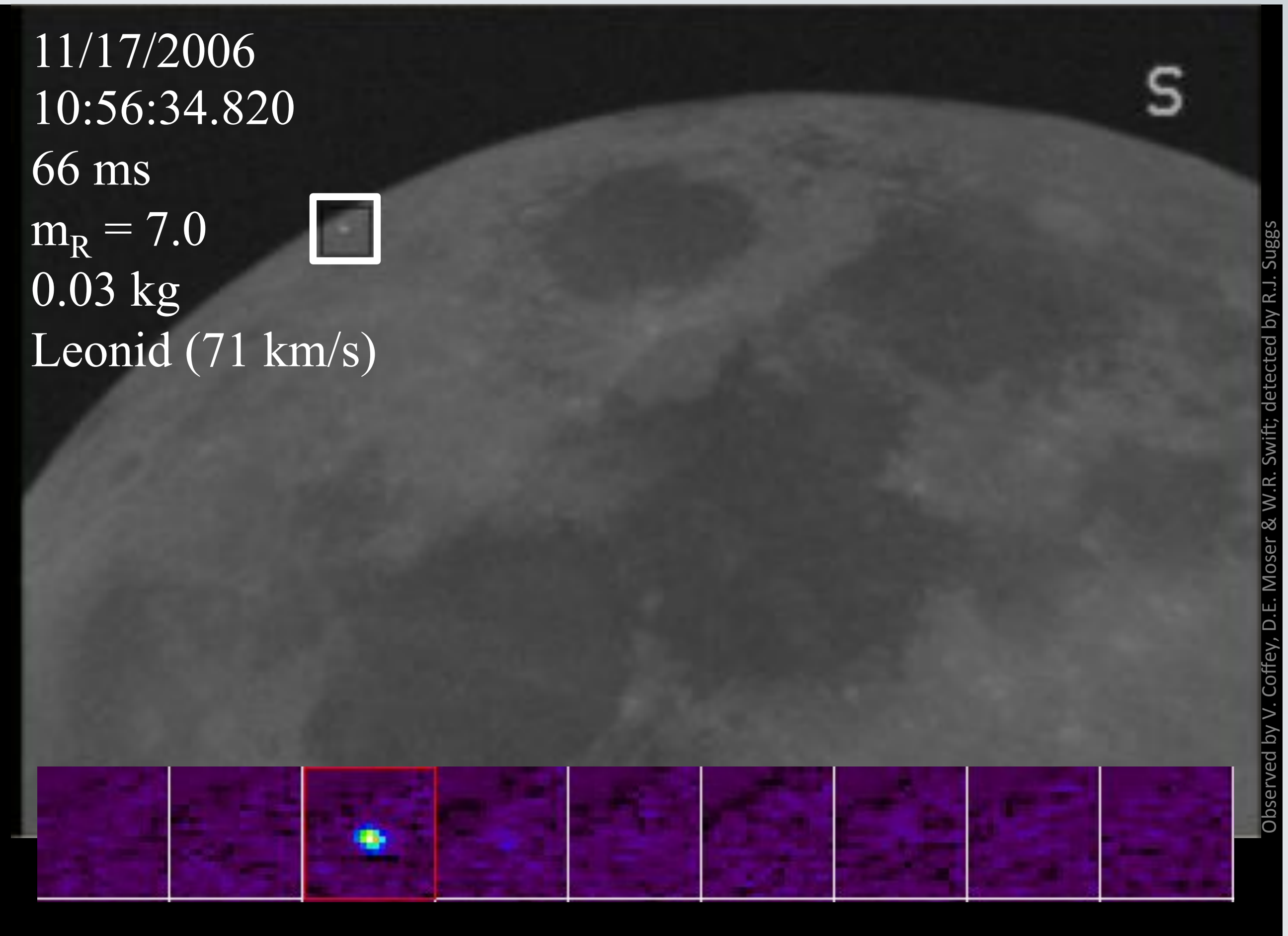
## 2005-present

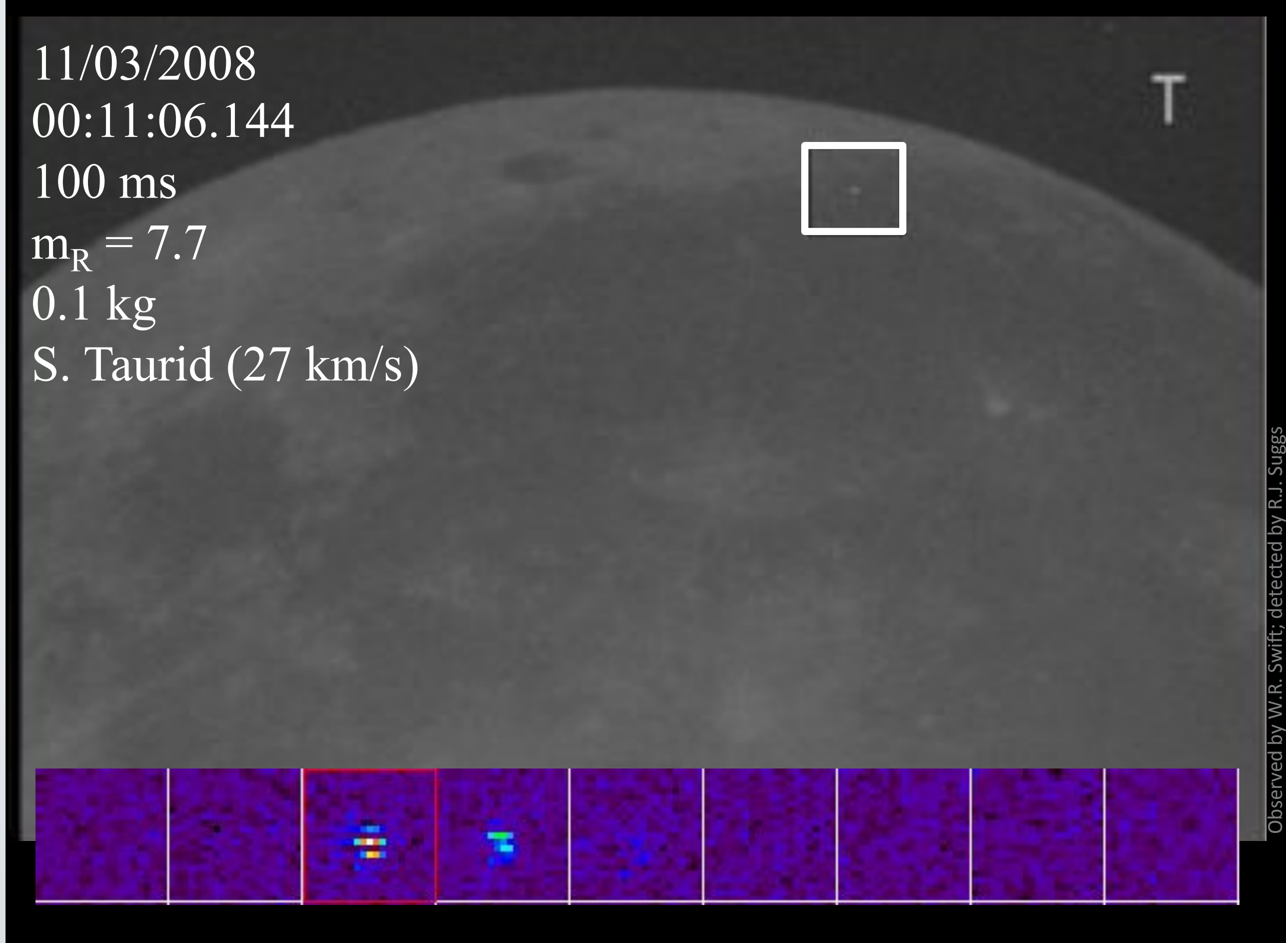


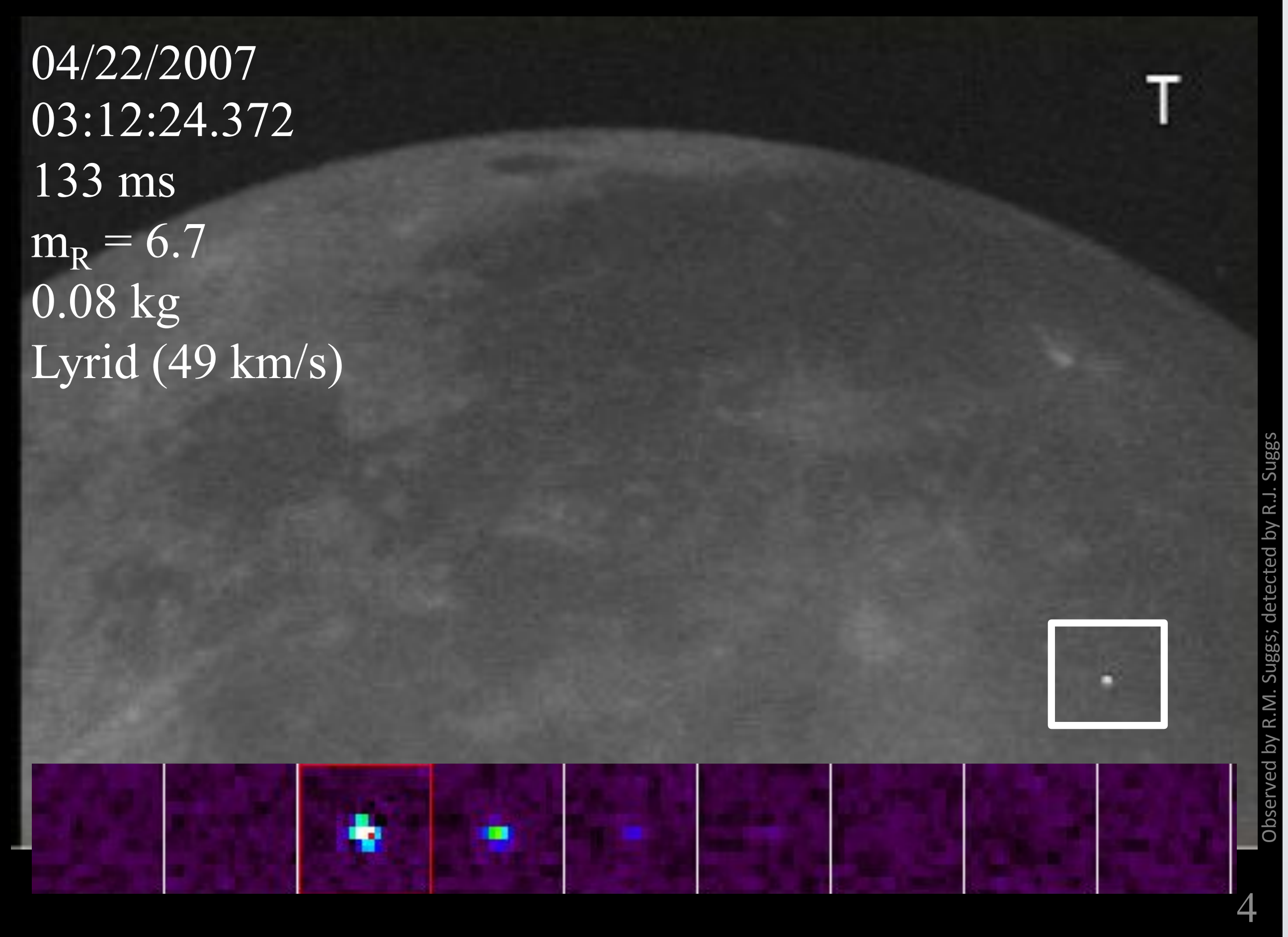
For more info:

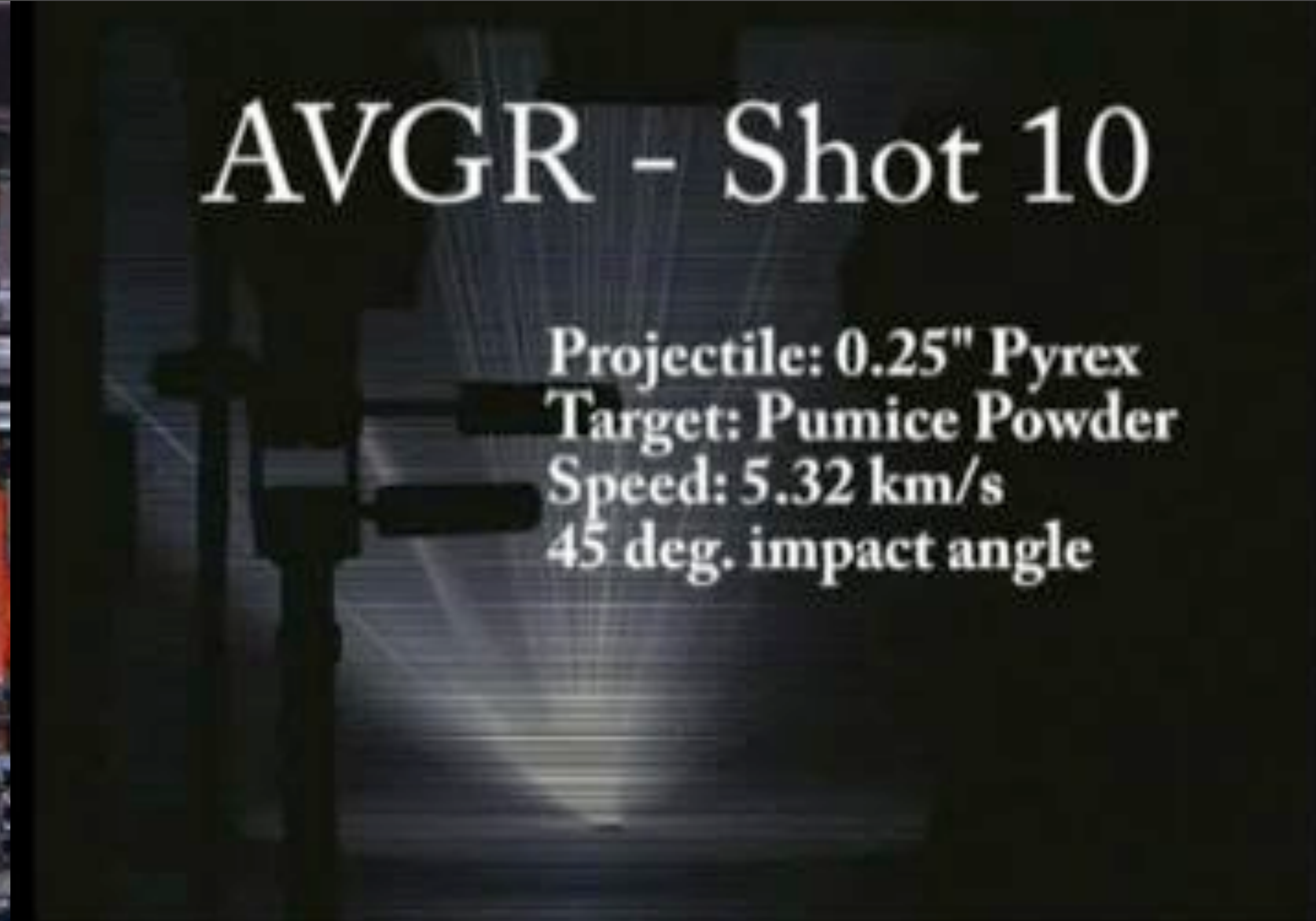
Suggs et al. (2013) to be submitted
Suggs et al. (2011)
Suggs et al. (2007)


12/15/2006
09:17:39.336
33 ms
$m_R$ = 7.4
0.09 kg
Geminid (35 km/s)
T
Observed by D.E. Moser & W.R. Swift; detected by R.J. Suggs


11/17/2006
10:56:34.820
66 ms
$m_R$ = 7.0
0.03 kg
Leonid (71 km/s)
S
Observed by V. Coffey, D.E. Moser & W.R. Swift; detected by R.J. Suggs


11/03/2008
00:11:06.144
100 ms
$m_R$ = 7.7
0.1 kg
S. Taurid (27 km/s)
T
Observed by W.R. Swift; detected by R.J. Suggs


04/22/2007
03:12:24.372
133 ms
$m_R$ = 6.7
0.08 kg
Lyrid (49 km/s)
T
Observed by R.M. Suggs; detected by R.J. Suggs



AVGR - Shot 10
Projectile: 0.25" Pyrex
Target: Pumice Powder
Speed: 5.32 km/s
45 deg. impact angle

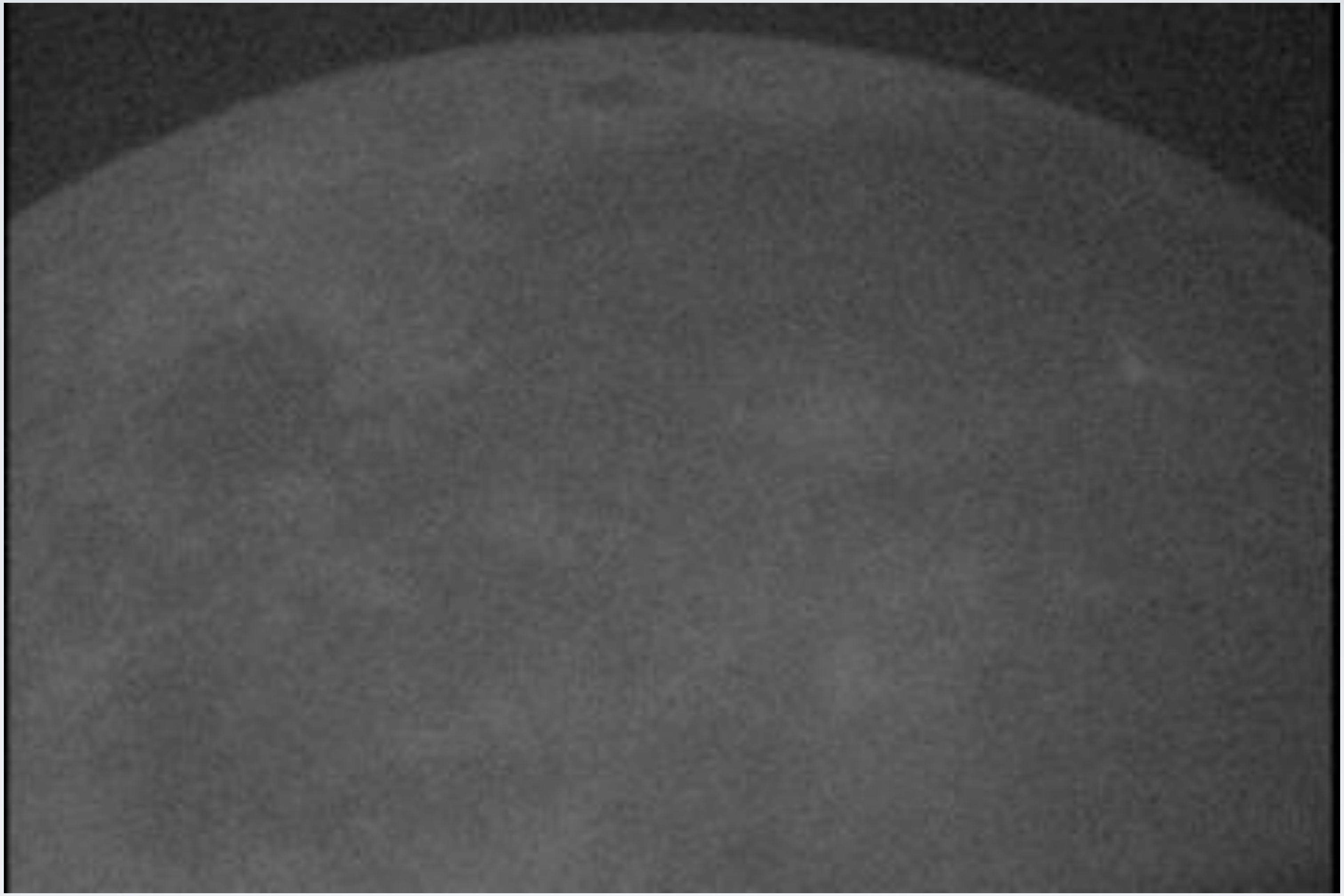

AVGR - Shot 10
Projectile: 0.25" Pyrex
Target: Pumice Powder
Speed: 5.32 km/s


011 00:04:712
NASA AVGR

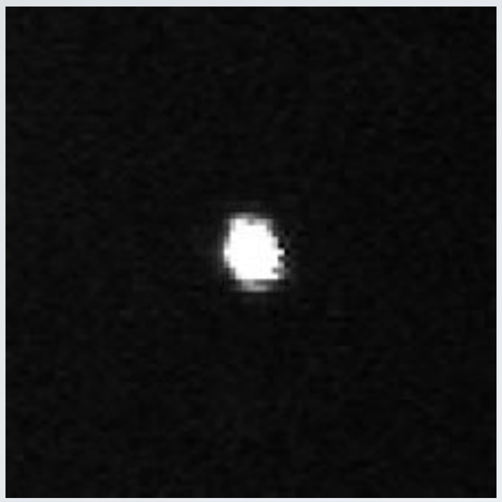
# March 17, 2013  3:50:54 UTC

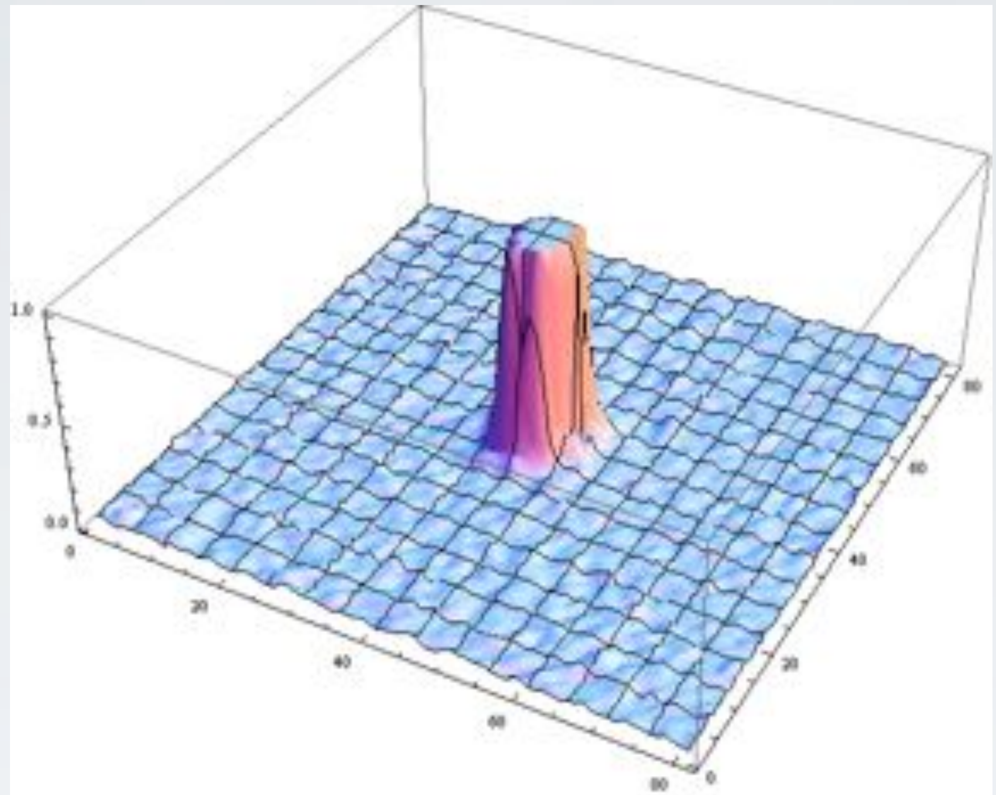

Observed by A. Kingery & R.M. Suggs; detected by R.J. Suggs

The brightest meteoroid impact flash detected in NASA's 7 year lunar observing program.



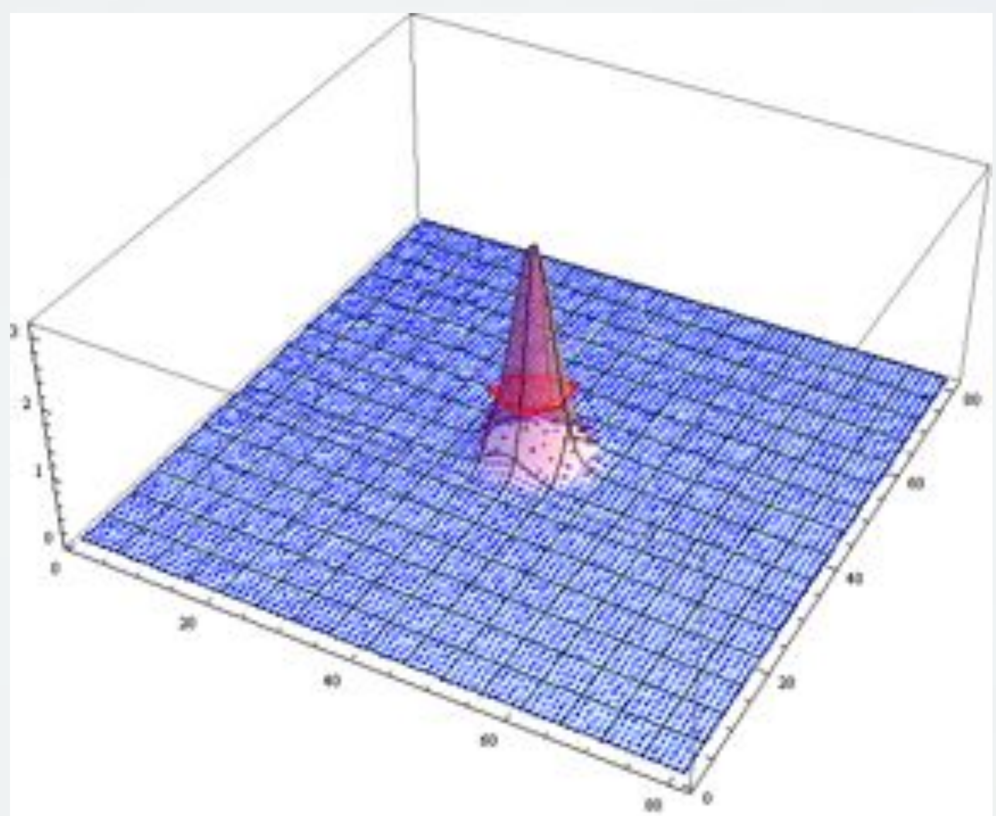
# Estimating the magnitude





Saturated

Peak $m_R = 4.9$



Photometry performed using comparison stars

2D elliptical Gaussian fit to the unsaturated wings

Peak $m_R = 3.0 \pm 0.4$

Similar results for
2D elliptical Moffat fit

# Preliminary energy estimate

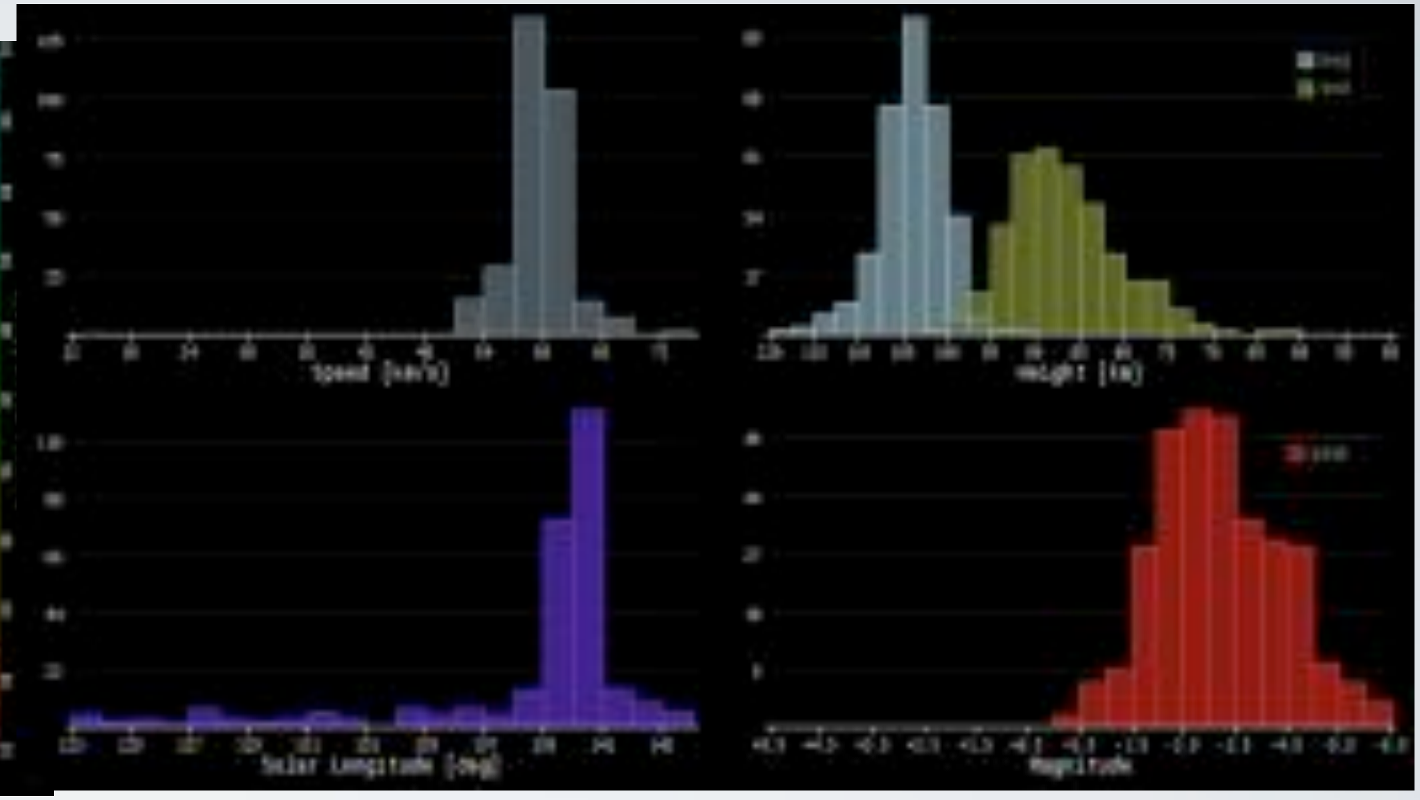
Luminous efficiency ($\eta_\lambda$) relates how much of the impactor's kinetic energy (KE) is converted to luminous energy (LE) in a wavelength range $\lambda$

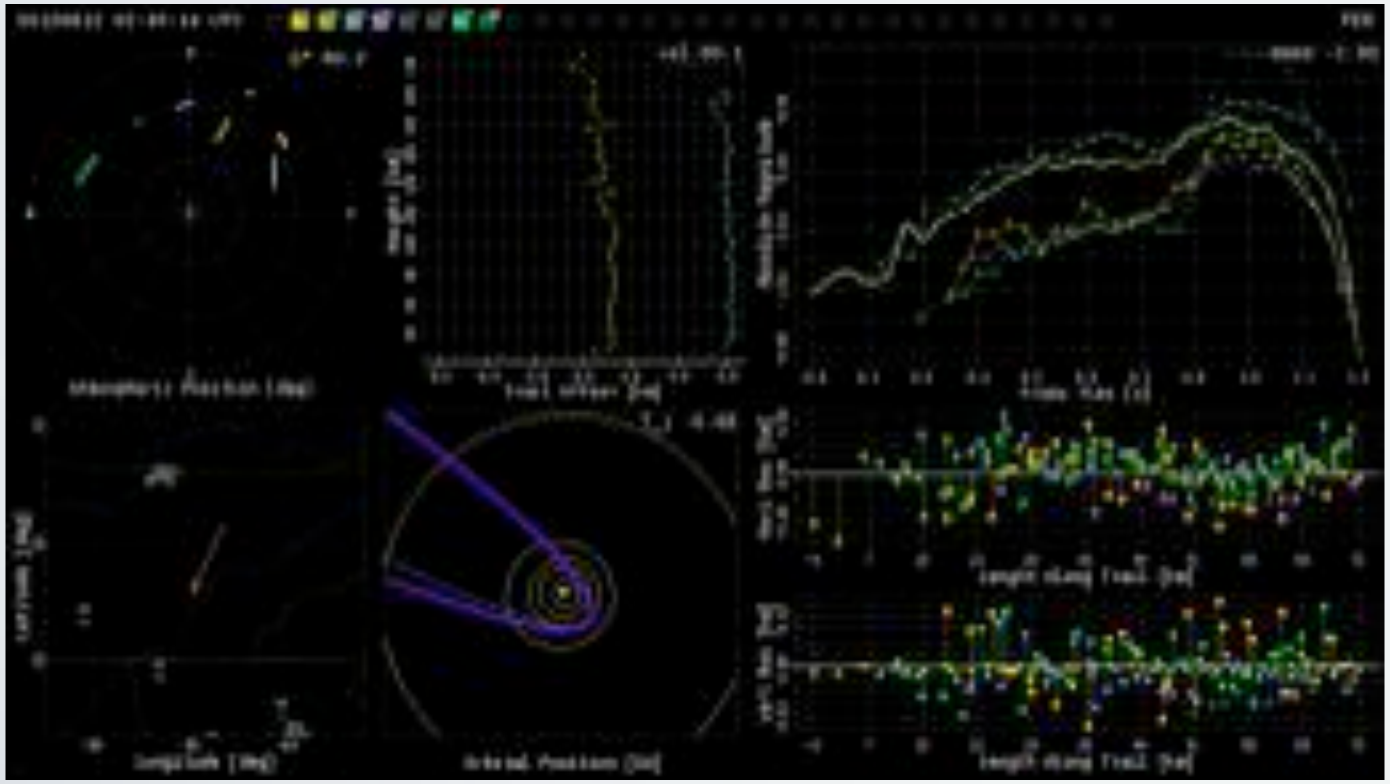
$$LE_\lambda = \eta_\lambda \, KE_\lambda$$

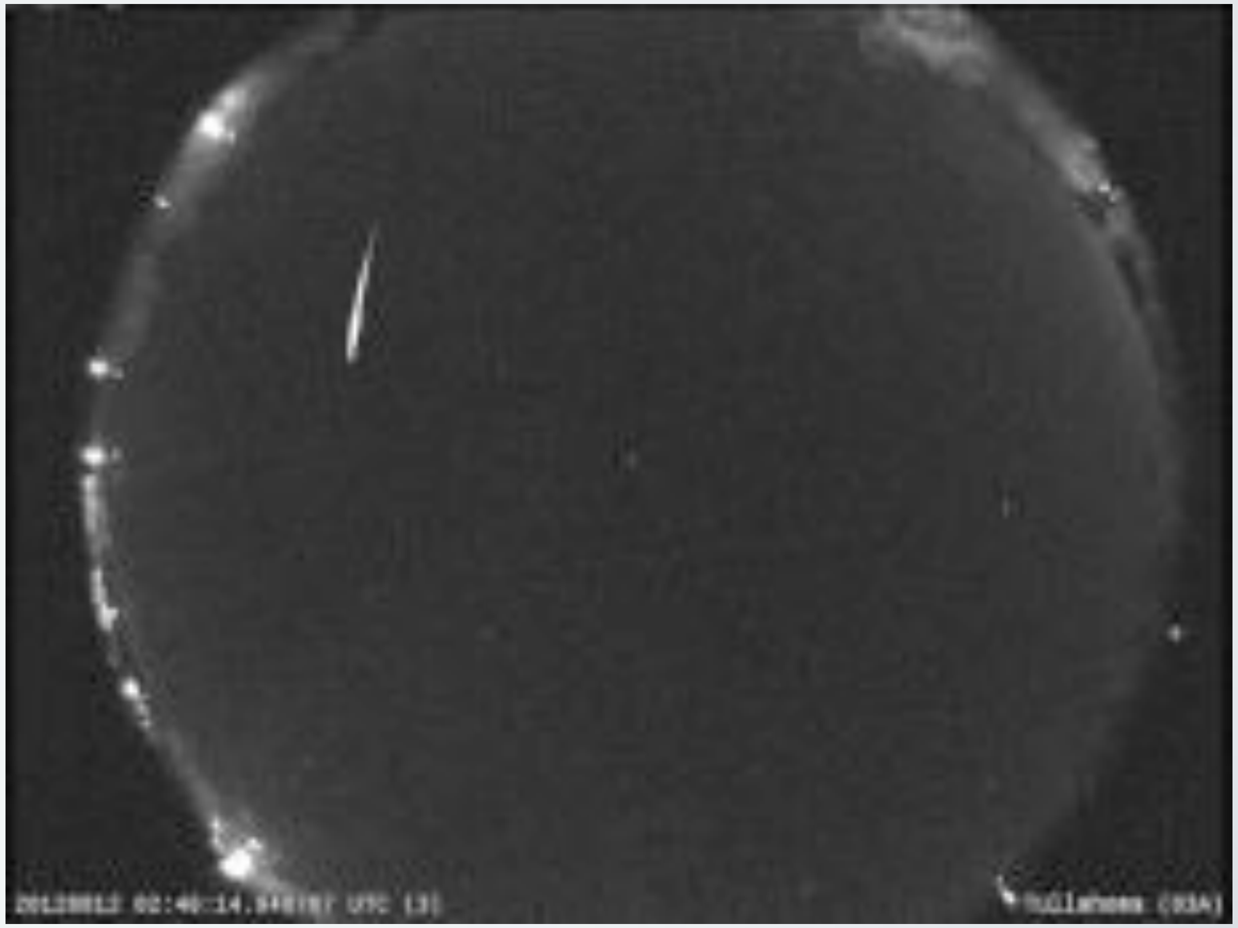
| | **Const. $\eta = 2 \times 10^{-4}$** | | **Vel. dep. $\eta = 1.3 \times 10^{-3}$** (Moser et al. 2011) | |
|---|---|---|---|---|
| | Average | Range | Average | Range |
| Luminous energy (J) | $7.1 \times 10^6$ | $4.7 \times 10^6 – 1.1 \times 10^7$ | $7.1 \times 10^6$ | $4.7 \times 10^6 – 1.1 \times 10^7$ |
| Kinetic energy of impactor (J) | $3.6 \times 10^{10}$ | $2.4 \times 10^{10} – 5.5 \times 10^{10}$ | $5.4 \times 10^9$ | $3.6 \times 10^9 – 8.4 \times 10^9$ |
| Impactor mass (kg) (assuming $v_g = 25.6$ km/s) | 108 | 72 – 168 | 16 | 11 – 26 |

Why did we assume $v_g = 25.6$ km/s?


Latitude [deg]
Longitude [deg]

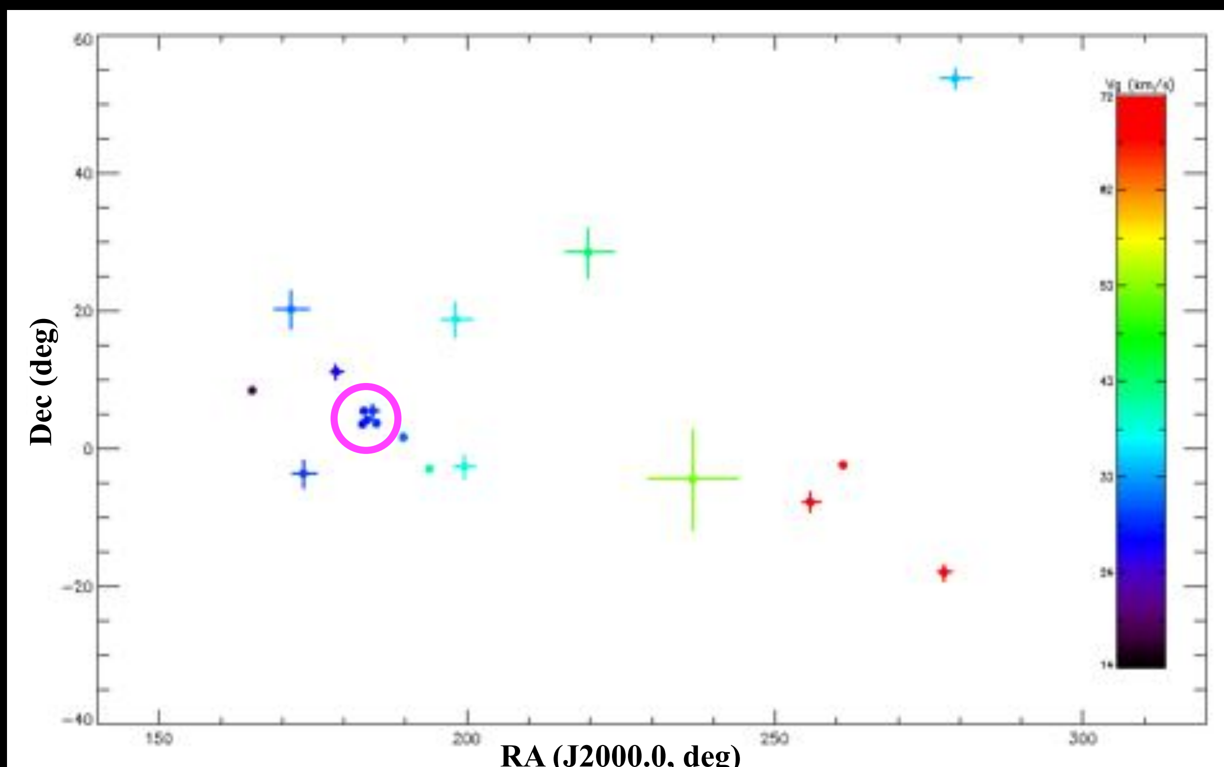

Speed [km/s]
Height [km]
Solar Longitude [deg]
Magnitude





# Meteor shower association

19 fireballs seen on Mar 17, 2013

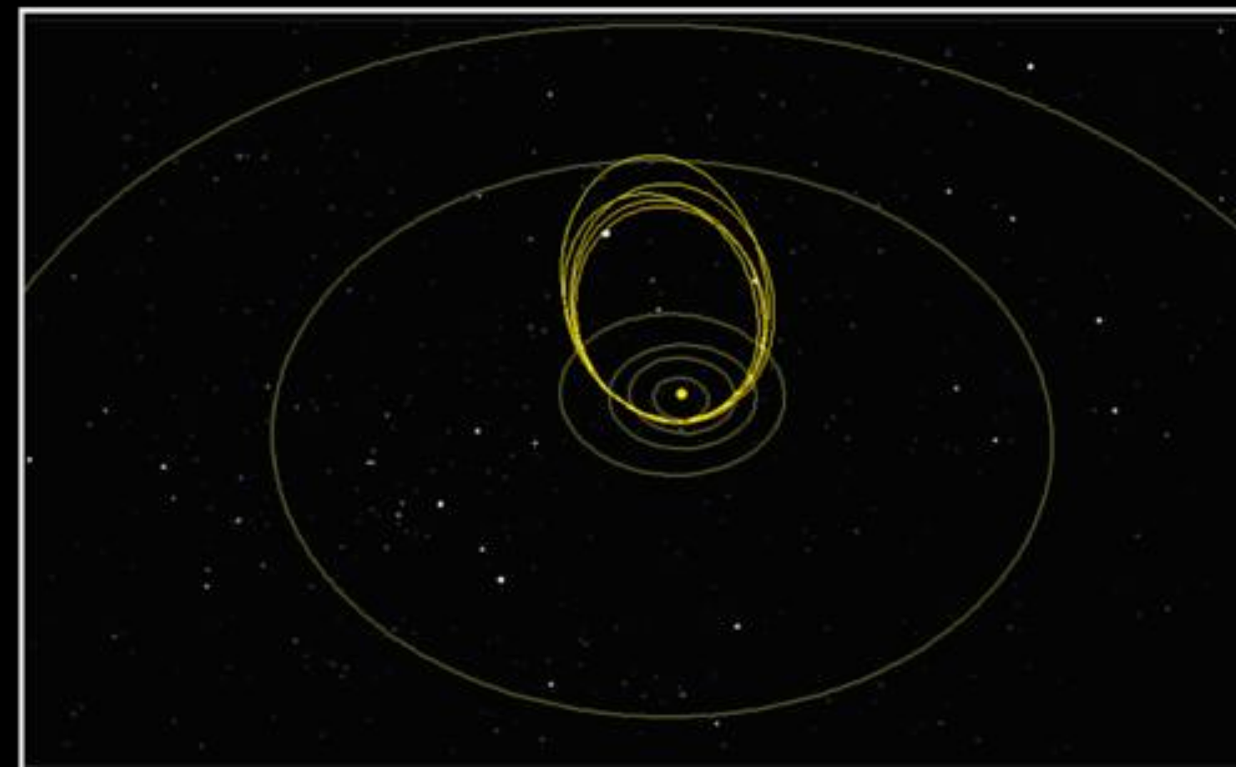



Geocentric meteor radiants color-coded by speed with a tight cluster of 5 with

| | | Virginid Complex | |
|---|---|---|---|
| | meteors | NVI[1] | EVI[2] |
| $\alpha_g$ (°) | 184.1 ± 1.0 | 185.7 | 183.6 |
| $\delta_g$ (°) | 4.4 ± 0.9 | 2.3 | 3.7 |
| $v_g$ (km/s) | 25.6 ± 0.8 | 23.0 | 28.9 |
| $\lambda_{sun}$ (°) | 356.6 | 354 | 354 |

[1](Sekanina, 1973), [2](Whipple, 1957)

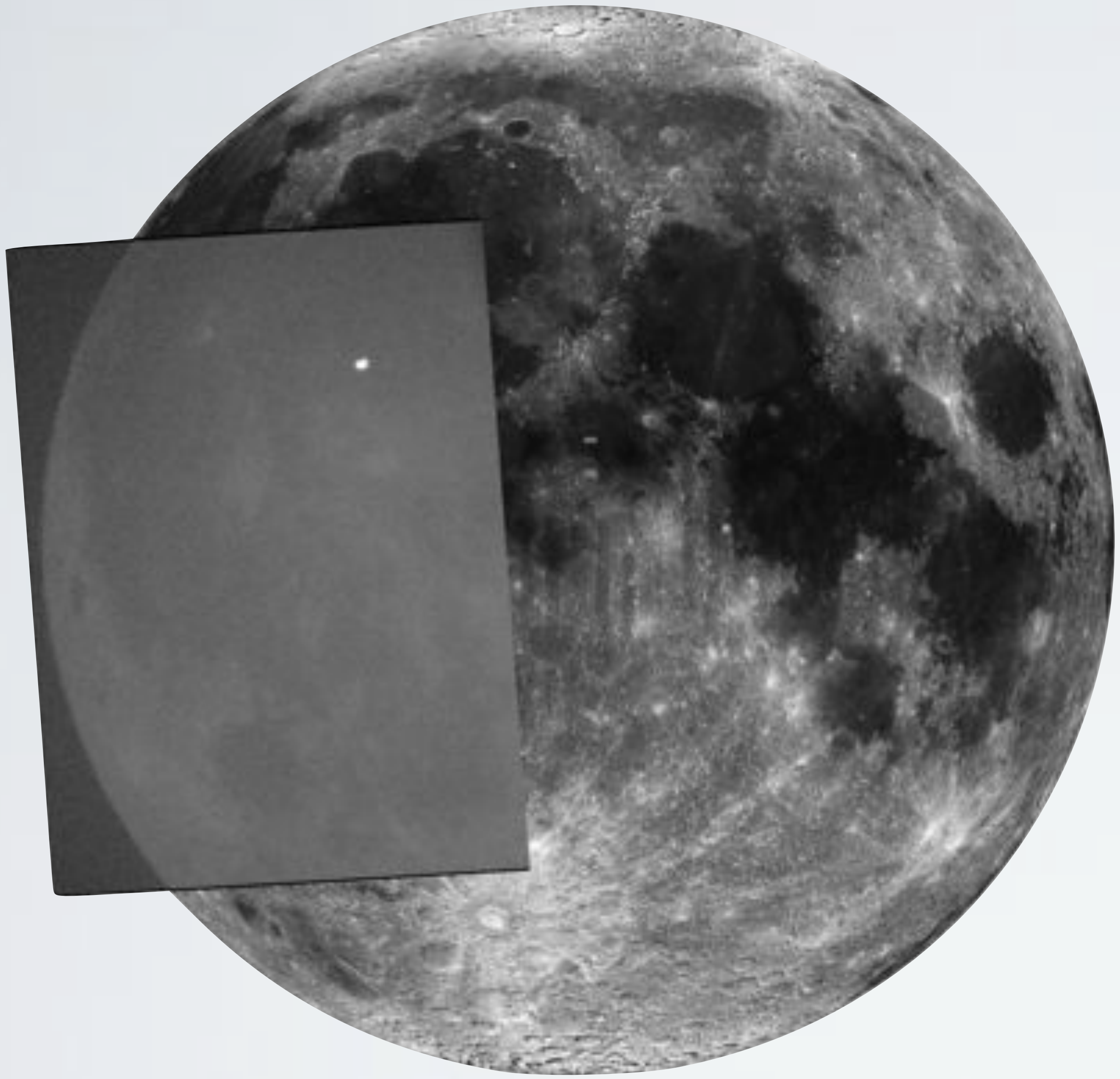
Cluster of 5 seen on Mar 17, 2013



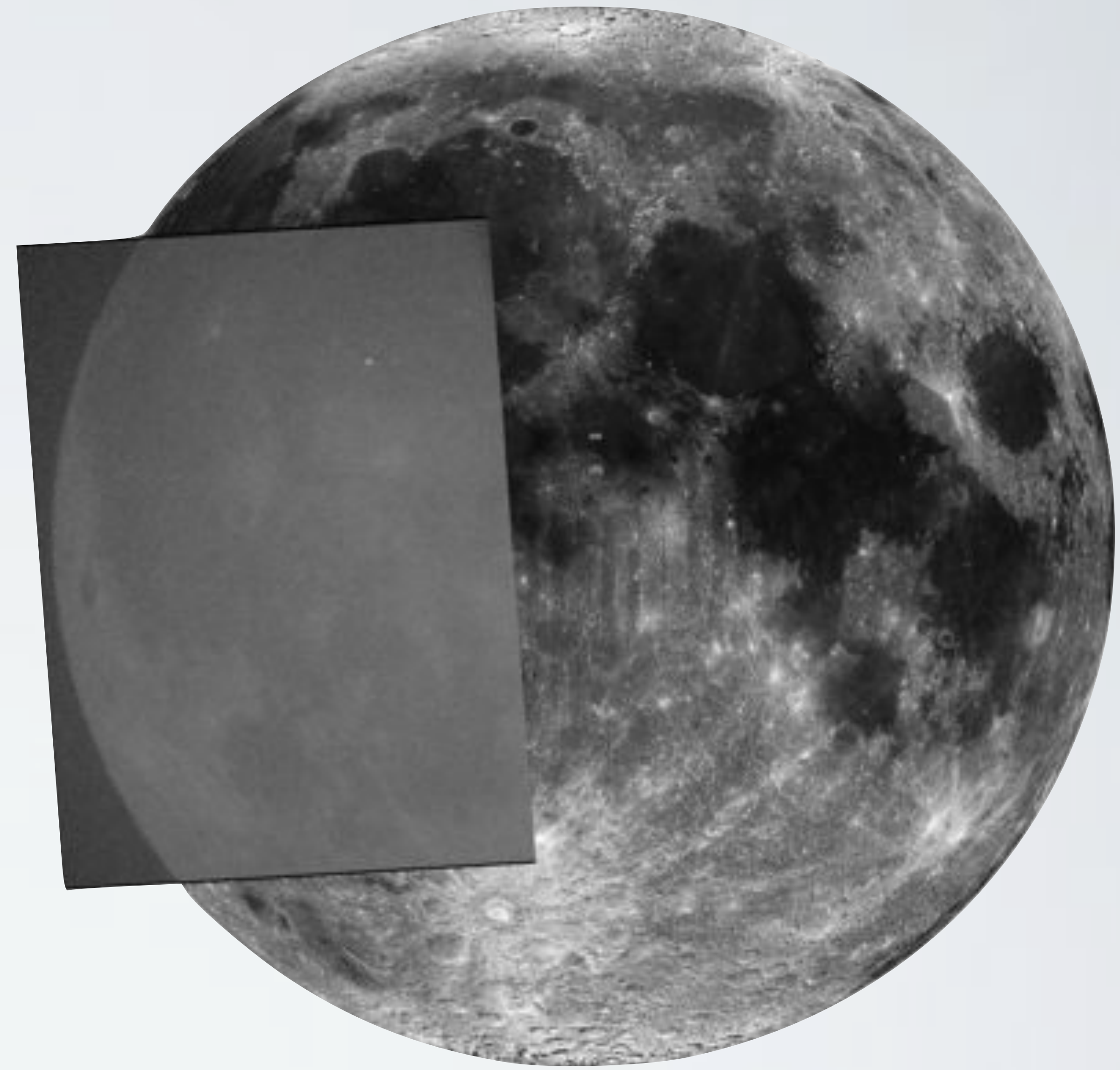
Orbits of the cluster of 5 were very similar with the following average orbital elements

| | meteoroids | NVI | EVI |
|---|---|---|---|
| a (AU) | 2.25 ± 0.17 | 1.69 | 2.82 |
| e | 0.79 ± 0.02 | 0.71 | 0.86 |
| i (°) | 5.26 ± 1.02 | 3.7 | 5.2 |
| ω (°) | 280.32 ± 2.11 | 282.4 | 285.8 |
| Ω (°) | 356.65 ± 0.07 | 358.0 | 355.1 |
| q (AU) | 0.48 ± 0.02 | 0.496 | 0.40 |
| Q (AU) | 4.0 ± 0.3 | 2.89 | 5.25 |
| Tj | 3.1 ± 0.2 → | Indicates asteroidal body | |

# Mapping the impact location

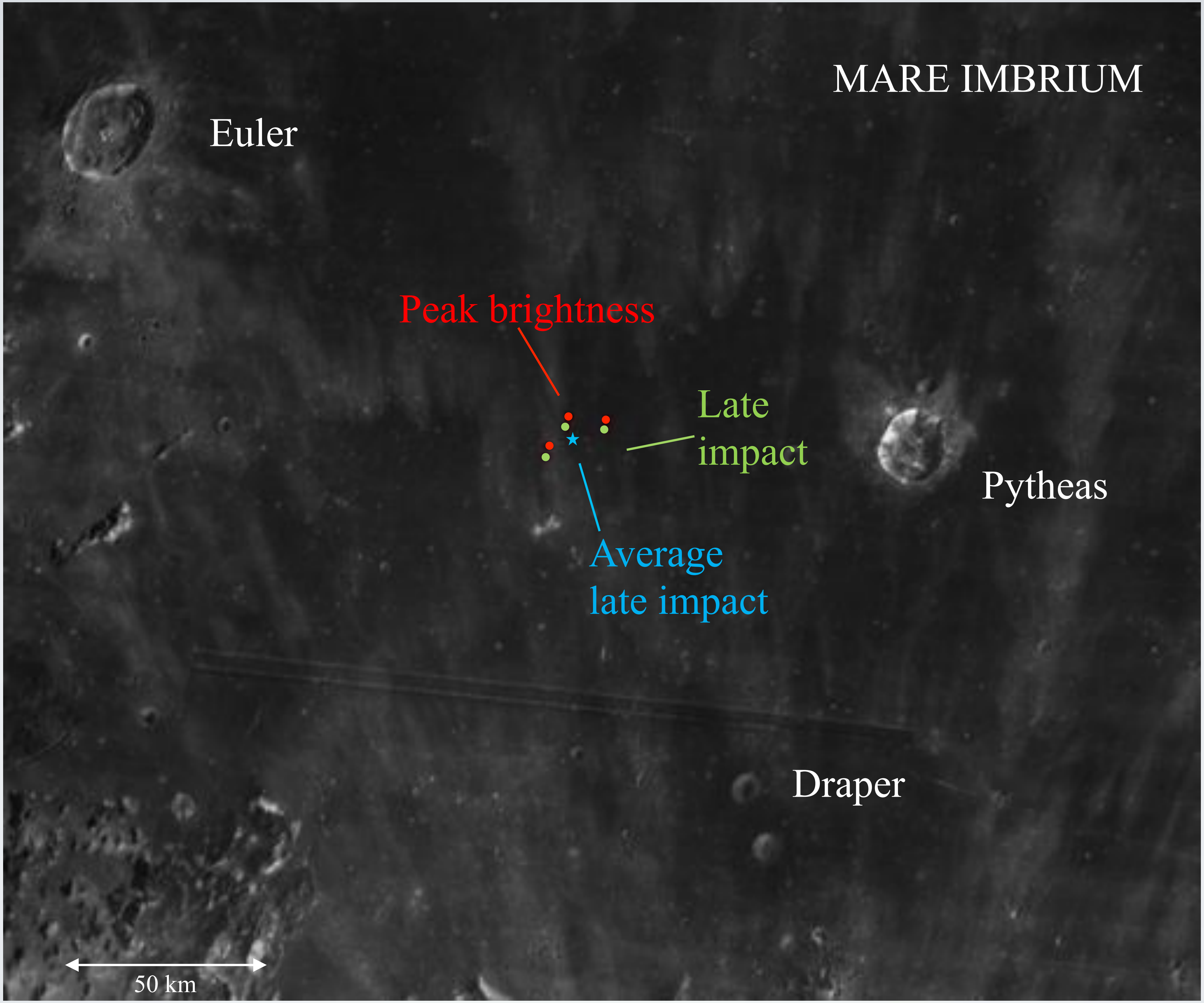


Flash at peak brightness

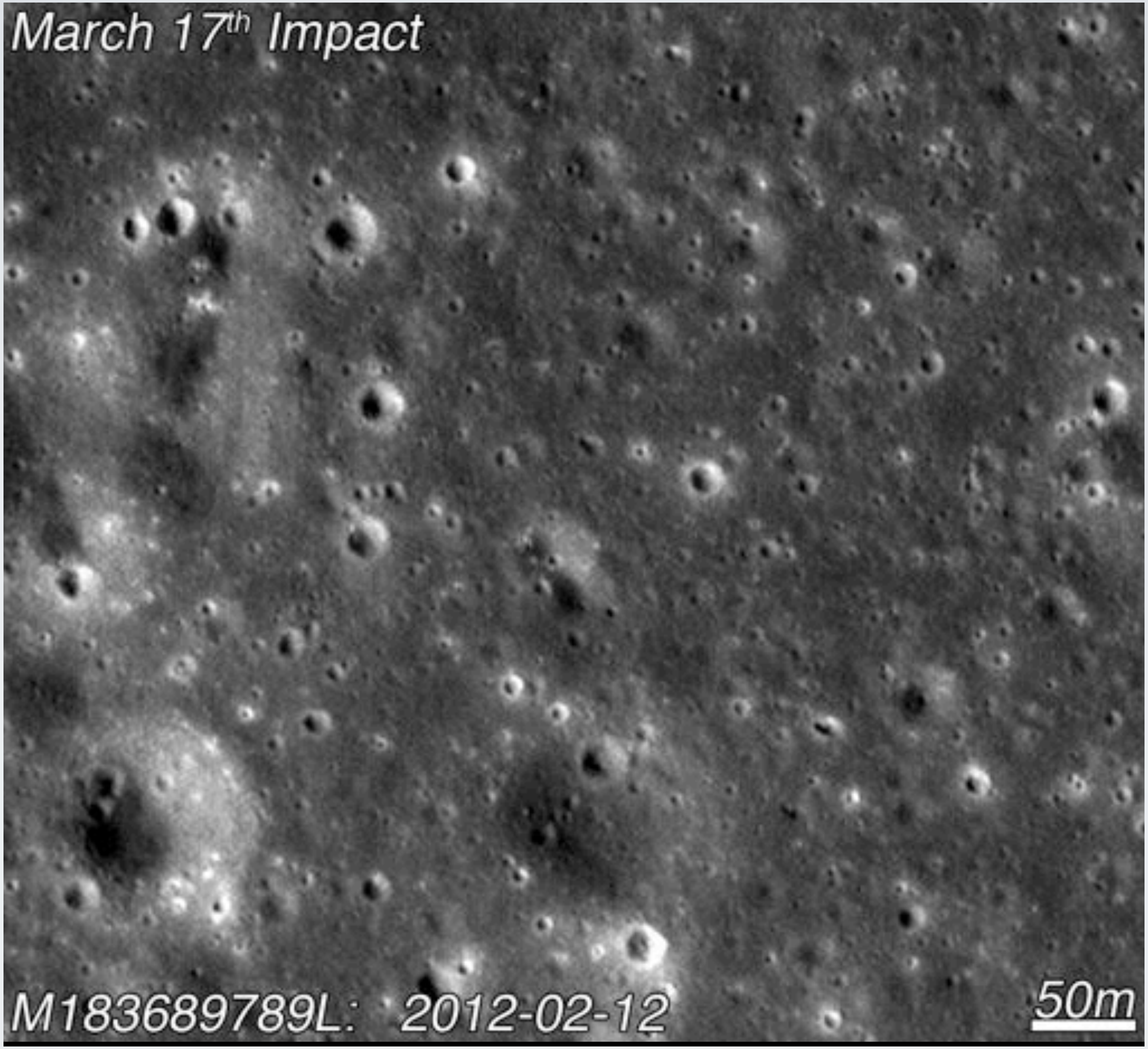


Flash 10 frames (333 ms) after the peak

ArcMap (ArcGIS 10) was used to georeference the lunar impact video



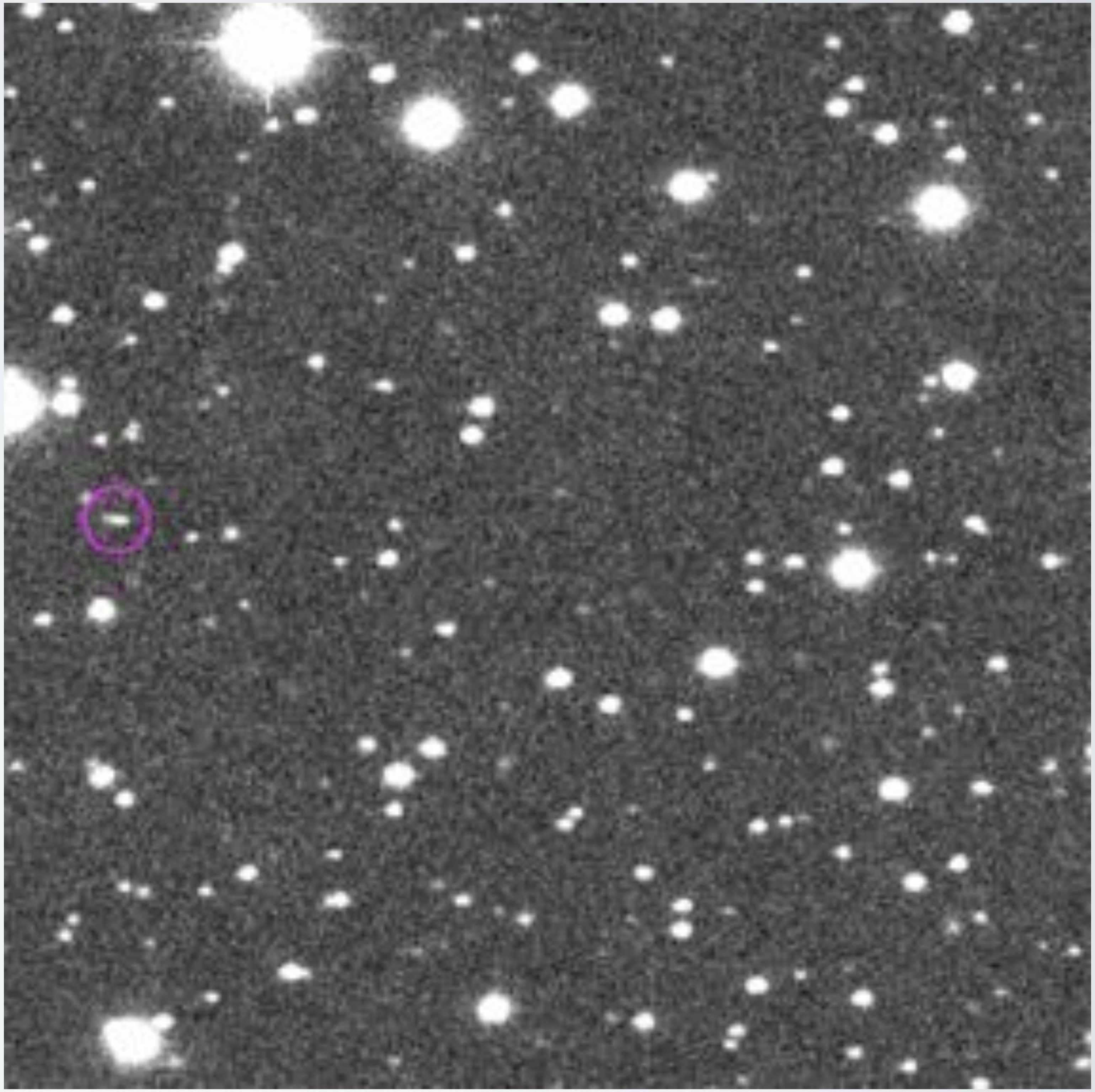

Average location: 20.599 ± 0.172° N, 23.922 ± 0.304° W


March 17th Impact
M183689789L: 2012-02-12
50m


March 17th Impact
M1129645568L: 2013-07-28
50m

# 2014 AA

Discovered January 1 at 6:18 UT. 7 images taken over 70 minute interval



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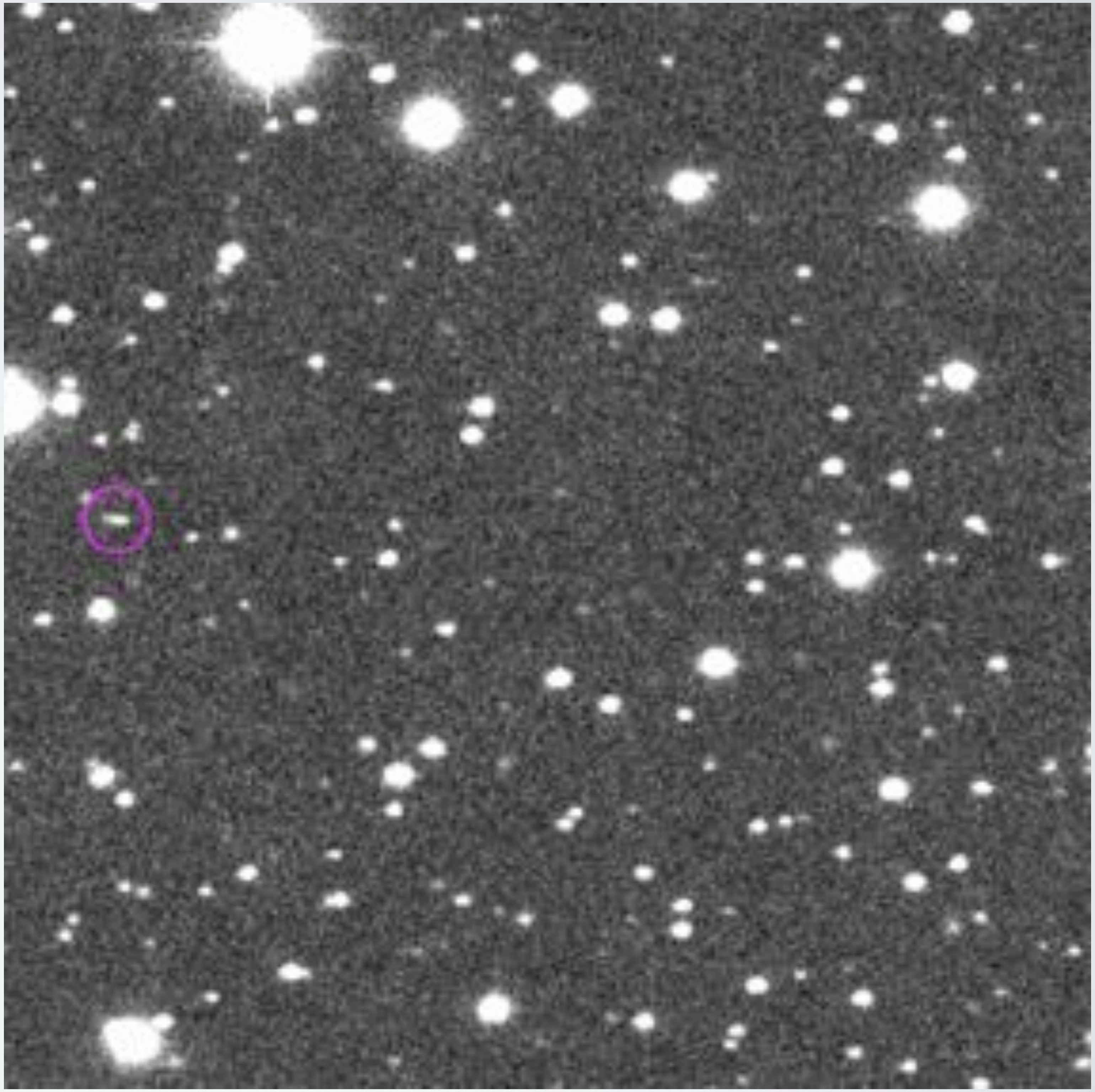
Magnitude of 19 indicated an object 2-4 meters in diameter



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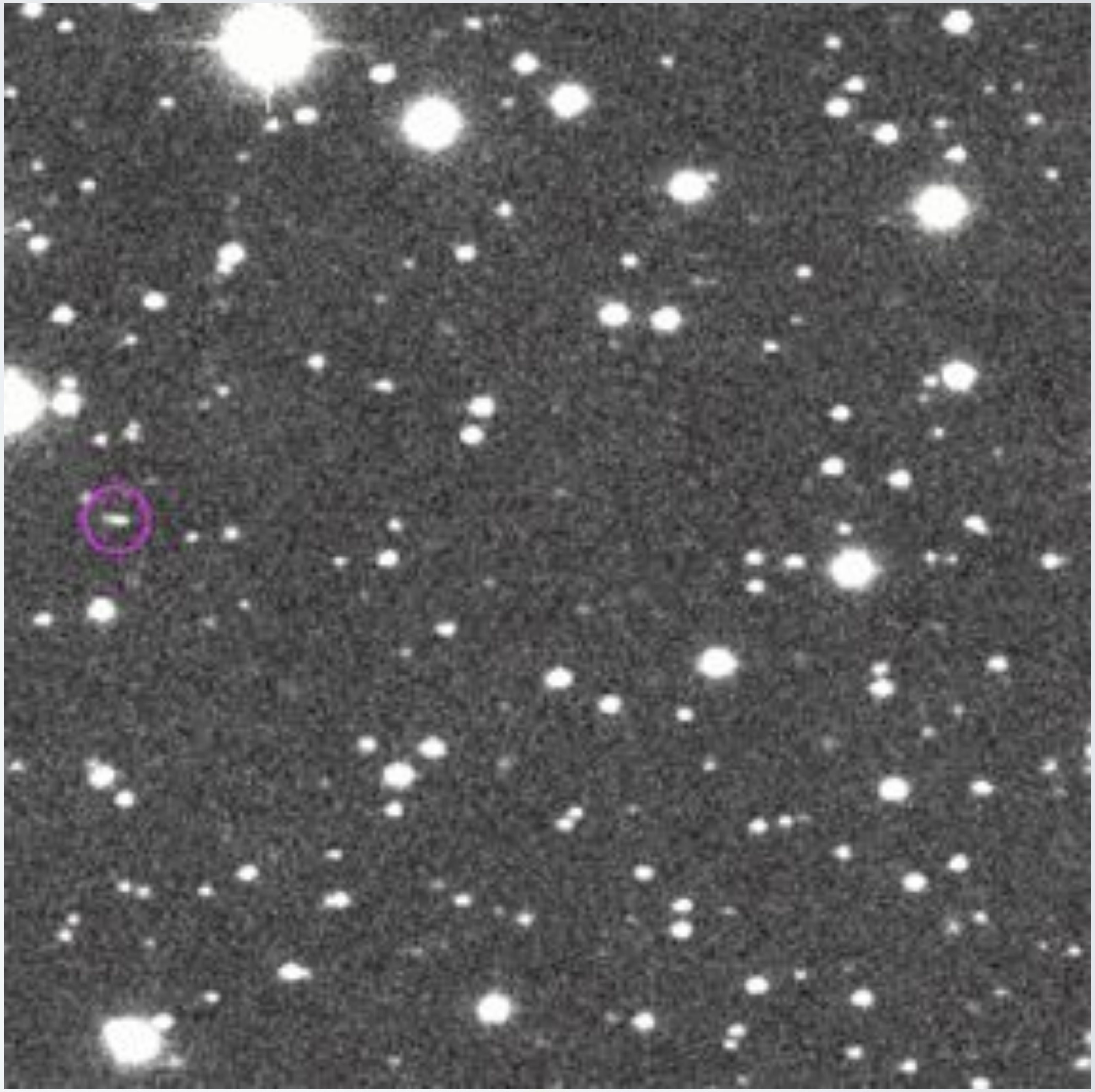
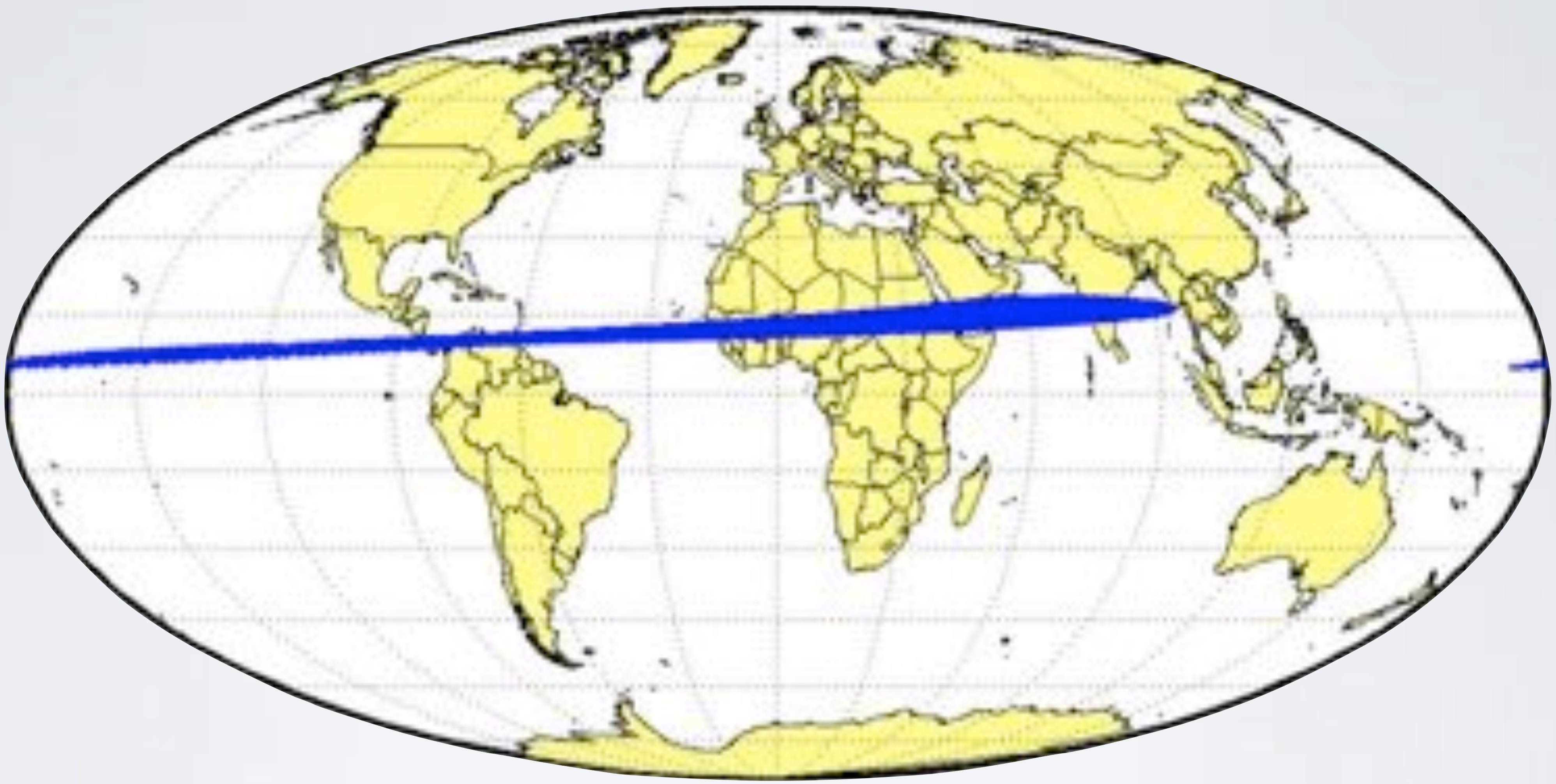
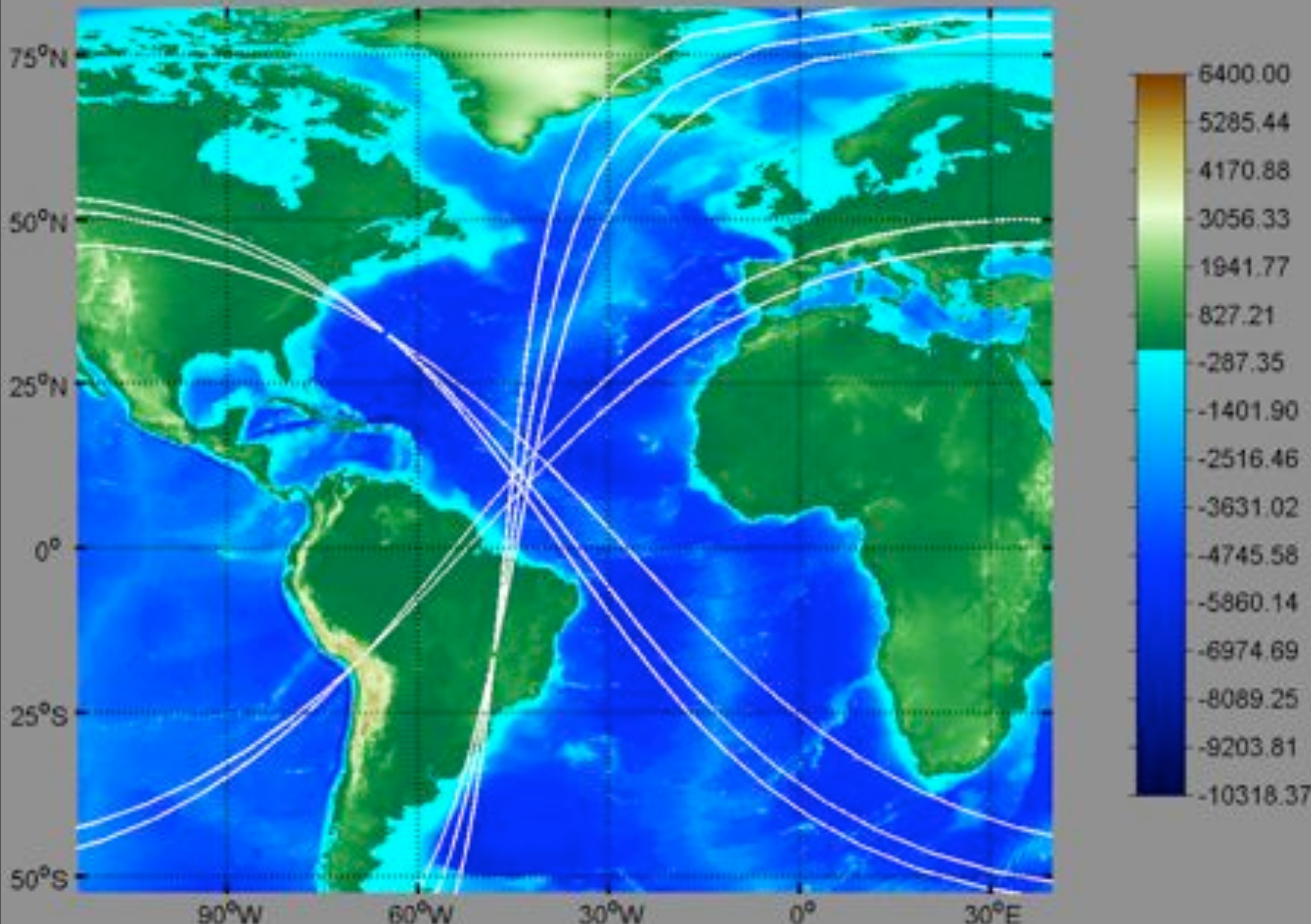
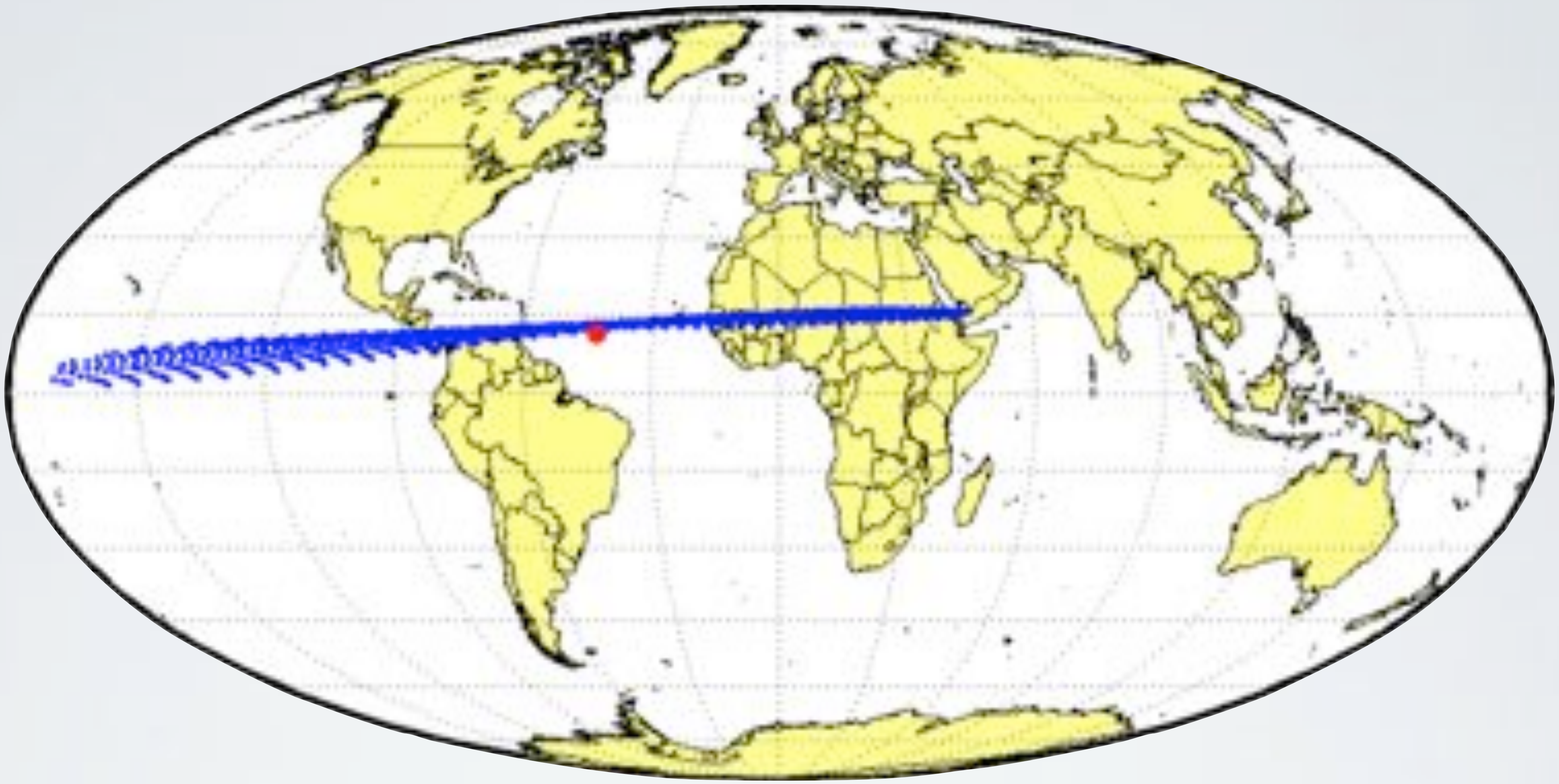
Positions submitted to the MPC, but no one realized object was on an impact course with Earth until just before impact





Projected impact time was Jan 2 2:25 UTC, just off coast of west Africa


75°N
50°N
25°N
0°
25°S
50°S
90°W
60°W
30°W
0°
30°E
6400.00
5285.44
4170.88
3056.33
1941.77
827.21
-287.35
-1401.90
-2516.46
-3631.02
-4745.58
-5860.14
-6974.69
-8089.25
-9203.81
-10318.37



Actual impact time was Jan 2 3:30 UTC +/- 30 minutes

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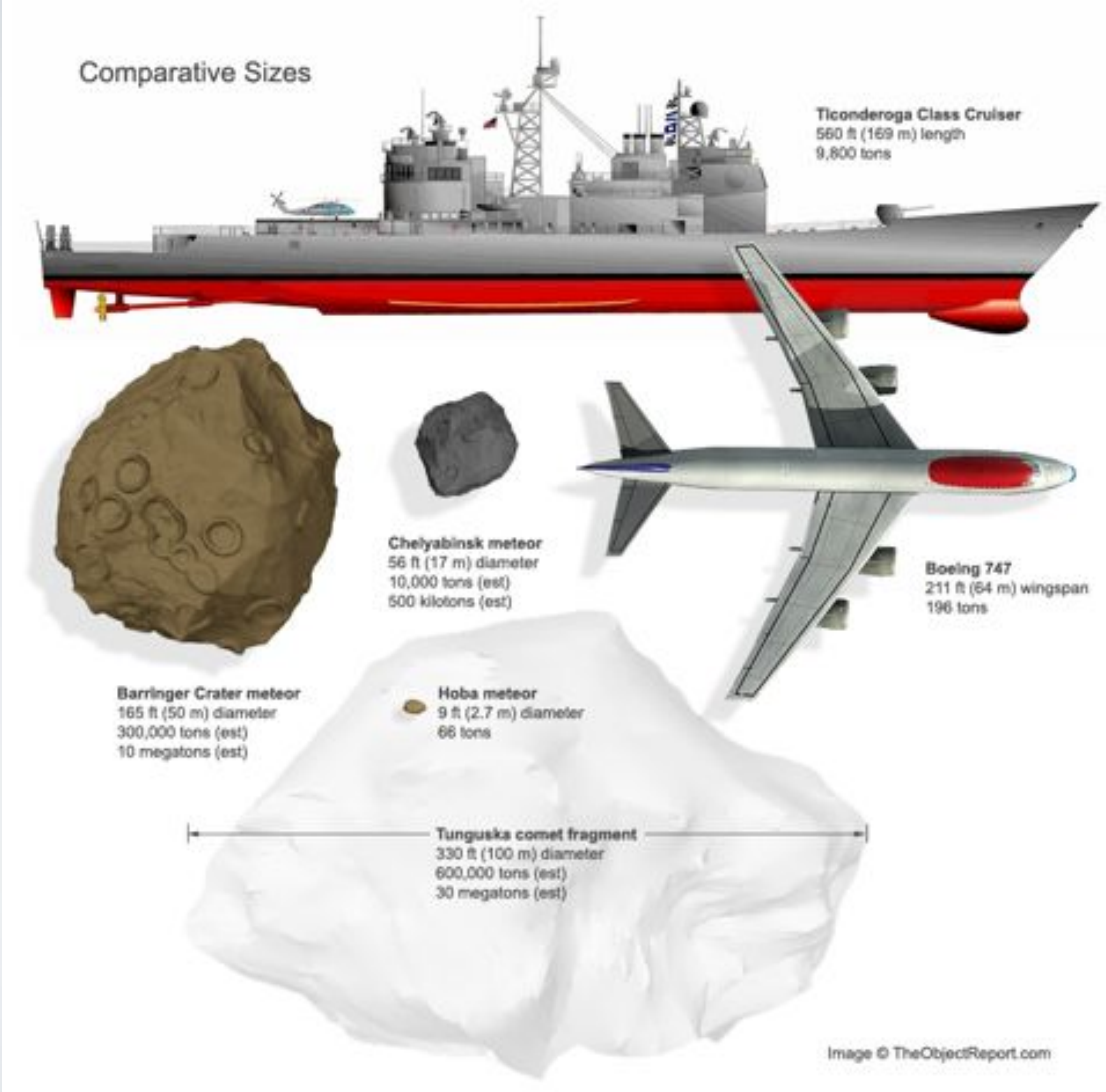
Impact energy of about 1 kiloton

# CHELYABINSK

## Fireball Properties

| | |
|---|---|
| **Energy** | 470 kilotons at altitude of 30 km (19 miles)<br>near Chelyabinsk (54.8° N, 61.1° E) |
| **Speed** | 19 km/s (42,500 mph) |
| **Mass/size** | ~12,000 tons<br>19 m (62 ft) |
| **Composition** | Ordinary chondrite (LL5) |


Comparative Sizes
Ticonderoga Class Cruiser
560 ft (169 m) length
9,800 tons
Chelyabinsk meteor
56 ft (17 m) diameter
10,000 tons (est)
500 kilotons (est)
Boeing 747
211 ft (64 m) wingspan
196 tons
Barringer Crater meteor
165 ft (50 m) diameter
300,000 tons (est)
10 megatons (est)
Hoba meteor
9 ft (2.7 m) diameter
66 tons
Tunguska comet fragment
330 ft (100 m) diameter
600,000 tons (est)
30 megatons (est)
Image © TheObjectReport.com


31.12.2012 18:30:40


Камера 2
8:44:55 15.02.2013


Камера 2
8:44:55 15.02.2013


CAM REC


Камера 2
8:44:55 15.02.2013

CAM REC



15/02/2013 09:22:32

# Kiloton Airbursts Detected by Infrasound: 2000-2013